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APPLICATION OF GEODETIC METHODS FOR MONITORING OF STRESSES OF PENSTOCK ON TEREBLYA-RIKSKA HYDROPOWER STATION

Summary

The long-term dependences for the changes of deformations and stresses in penstock based on the results of many-year investigations are established. Such investigations were held on the spatial geodetic network on the Tereblya-Rikska hydropower station (HPS). The investigations of the short-term stresses and deformations of the penstock with the use of electronic tacheometer Leica TPS 1201 has been undertaken. Direct correlations between the changes of the length of all baulks and the changes of water level in the storage reservoir are determined

Key words: geodetic methods, hydropower plant, penstock stress

PROBLEM RAISING AND ITS CONNECTION WITH IMPORTANT PRACTICAL TASKS

Peculiarities of building of hydropower station (HPS) require continual geodetic and geophysical control on endogenous processes of adjacent territory and as consequence on deformational processes of engineering constructions. Derivational HPS are created usually in mountain regions as for their functioning it is necessary the availability of considerable relief level difference.

All mountain rock formations coincide with zones of tectonic disturbances and most active breaks. Reservoirs created artificially for HPS functioning contributes to disturbances of hydrologic state of territory and appearance of hydrodynamic loads in the zones of tectonic breaks. It is known [Nikonov, 1984] that when additional hydrodynamic load of water mass penetrates into the faultzones then it decreases the friction between tectonic blocks what activates their dynamics. So it can be a reason of seismotectonic processes. Engineering constructions located in the zones of tectonic blocks undergo deformational loads as a result of block activity.

A lot of cases of consequences of tectonic and hydrodynamic loads influencing the stability of constructions are known in the engineering practice. On the Nurekska, Rogunska HPS (Tadjikistan), Toktogulska HPS (Kyrgyzstan), Inguri HPS (Georgia), the influence of hydrodynamic loads of storage reservoirs appears within the radius of several kilometers around the storage reservoir [Rayzmann, 1990; Ustinov, 1994; Antonov, 1983], and amplitude of spatial displacements of geodetic network points achieves 45 mm. Additionally, the correlation of vertical displacements of benchmarks appears when water level in storage reservoir changes.

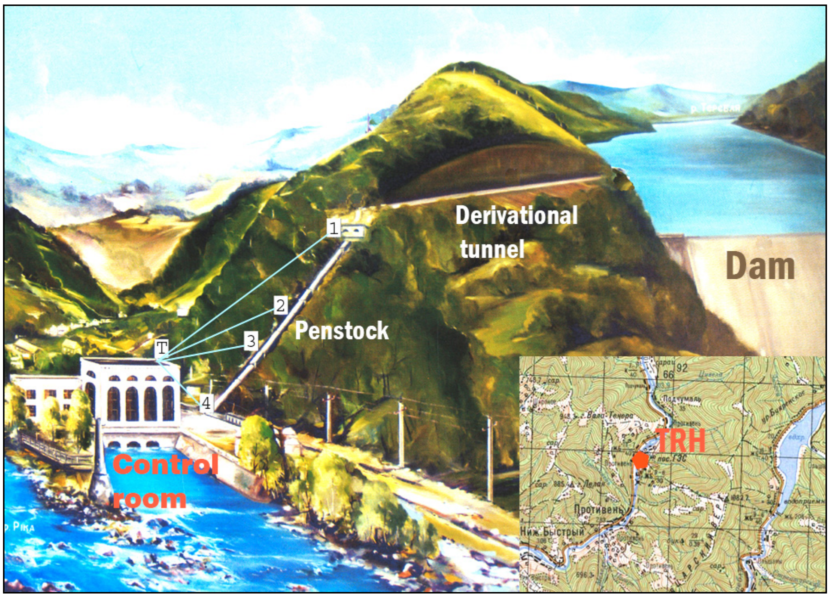
Similar regularities are observed near Villujsk storage reservoir (Lithuania), Quebec storage reservoir (Canada), cascades of reservoirs in Poland, Asuan dam (Egypt), where velocity of vertical movements of the earth surface is up to 7 mm per year and displacements of benchmarks are up to 40 mm [Turiy, 1976; Lambert et al, 1986; Tsatson and Dyyor, 1988; Vyskocil et al, 1988]. Often, when water filla up a storage reservoir, stresses are observed in mountain rocks and above described seismicity appears, as for example on the storage reservoir “Three Gorges Dam” in China [Wang et al, 2002].

Tereblya-Rikska hydro power station (TRHPS) is located in the Carpathians, 35 km north from the district center Khust in the Transcarpathian region of Ukraine. TRHPS is a hydro power station of derivational type. Selection of its location was determined by specific geomorphologic conditions existed between the rivers of Tereblya and Rika. From geomorphologic point of view it is a single place in the Carpathians where the difference in elevation of two river beds is more than 200 meters and the distance between them is about 4 km. Building of TRHPS was started in 1950 and during 1954-1956 was set in operation. The dam with length 153 m and height 45.8 m was constructed on the river Tereblya. The storage reservoir area is 15.5 km^2, and volume 23.6 million m^3. Between rivers Tereblya and Rika the derivational tunnel with length 3.7 km was built. Water from filled storage reservoir flows via the derivational tunnel to the penstock and then to the generator. In such way, water is flowing to the river Rika trough Tereblya-Rikska HPS. Maximum water use is 18 m^3/sec [Tereblya-Rikska HPS 50, 2006].

ANALYSIS OF RECENT INVESTIGATIONS AND PUBLICATIONS RELATED TO THIS PROBLEM

Auspicious geomorphologic conditions of the HPS territory are determined by the activity of the Rikskyy tectonic break in the past. According to the results of the geological-geomorphologic researches, the tracing of the Rikskyy tectonic break coincides with the axis of the dividing range of rivers Tereblya and Rika [Demedyuk and Tretyak, 1992]. Partial destroying of derivational tunnel on the axis of the dividing range determined during its investigation in 1998 confirms the modern activity of the tectonic break.

The modern tectonic activity of the region and also some peculiarities of the main HPS constructions, especially penstock, require continual geodetic control of possible deformations.



1, 2, 3, 4 – geodetic points on the anchor supports of the penstock; T – observation station.

Figure 1. Scheme of the Tereblya-Rikska HPS

Geodetic observations of main constructions of TRHPS started in 1958 and were implemented according to the observation programs with certain cyclicity. Special attention was paid to the metal penstock with length of 350 m. Difference of altitudes of the beginning and the end of the penstock is about 162 m. The penstock lies on four anchor supports and some intermediate supports. The anchor supports were laid into ledge rock on the depth from 10 to 209 meters from the land surface. Slope angle of the penstock is within the limits 20º-36º (fig. 2). In the past methods of triangulation and geometric leveling were used for investigation of displacements of anchor supports of the penstock.

However, the method of geometric leveling is not economically proved because of considerable level differences between the supports and is technically unreliable because of fixing of leveling lines with temporary benchmarks on landslide slopes. Nonsimultaneous triangulation and leveling works are additional disadvantages of this method. Therefore horizontal and vertical displacements determined by this method are nonsynchronous. So for determination of spatial deformations of the penstock the method of linear spatial cinematic geodetic networks was applied which do not have above described disadvantages.

Measurement schemes in such networks depend on conditions of terrain. In the case of using optical range finders for line measurements the use coupled systems of spatial linear intersections is most appropriate. In Fig.2 the scheme of spatial network created on the TRHPS is shown. Until 1989 the goniometrical measurements were undertaken on the network points, and they enabled to fix only horizontal displacements of the penstock [Demedyuk et al, 1998]. Totally, during this period 37 repeated cycles of observations were done. Since 1989 till 2000 the works are undertaken on enlarged kinematic spatial network with application of optical range finders measurements. It enabled to fix simultaneously horizontal and vertical displacements. Optical range finders SP-2 was used for the measurements. Eight cycles of observations were done. Since 2000 and till now the observations have been undertaken using a GPS-method and combination of optical range and GPS measurements. GPS-receivers Leica SR-9500, SR-399 are used with applying static technology of the measurements. Application of abovementioned methods of observation enables to reach such precision of determination of changes of point elevation that practically corresponds to the precision of the leveling of class *II*. 12 cycles of observations were implemented. Totally, 60 cycles of measurements were made.

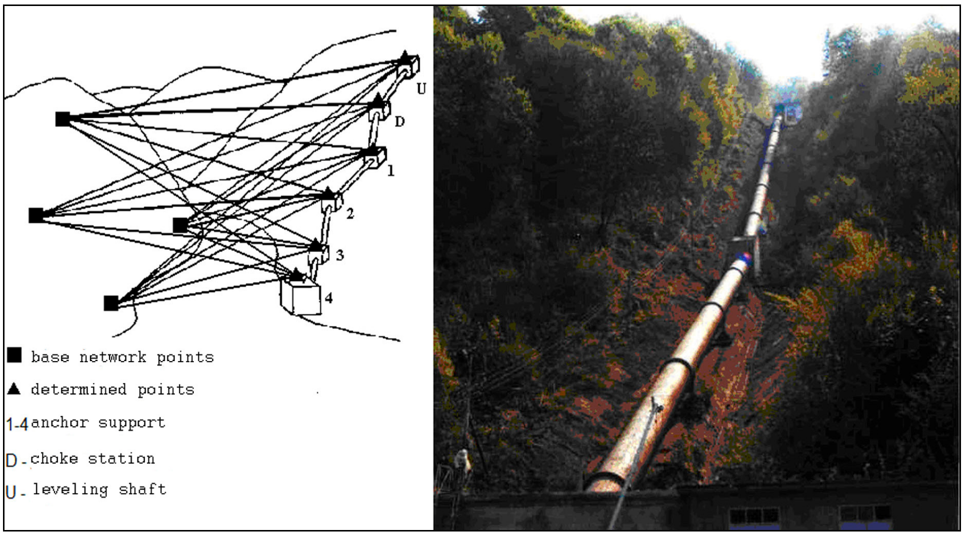


Figure 2. Scheme of linear spatial geodetic network of the penstock of TRHPS

During the period 1959-1988 horizontal displacements of anchor supports were within 8.0 – 10.4 cm (Fig.3), and vertical displacements were within 14.2–17.7 mm. Application of optical range and GPS measurements enabled to determine parameters of deformation components γ_x, γ_y, γ_z, γ – relative displacements of the penstock baulks on axes *X, Y, Z*, and general displacement Δ – dilatation (compression and tension).

Since 1989 till 2007 the dilatation was within 0.003407 – 0.00183. Fig. 4 shows the spatial-time distribution of the displacements Δ during 1989-2007.

On the left vertical axis the distances along the penstock from the center of the upper baulk are shown. On the right vertical axis there are shown the positions of baulk weight centers. Lower horizontal line corresponds to time of observations. Distribution of dilatations is shown in dimensionless isolines.

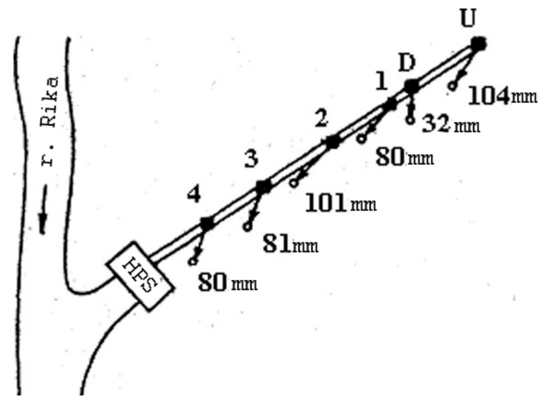


Figure 3. Vectors of general displacements of supports of the penstock during 1958–1989

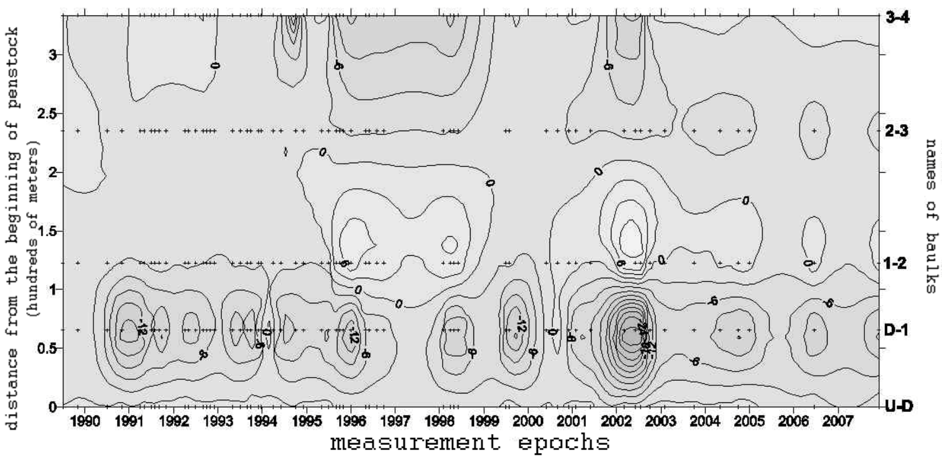


Figure 4. Spatial-time distribution of the relative displacements Δ
(isolines are drawn in $2 \cdot 10^4$)

On the diagram we can see that maximum dilatation (of compression) lies in the zone of joint of derivational tunnel and penstock.

Lets divide fixed displacements and stresses into the background and local ones. The background displacements (shown in Fig. 3) cause general displacement of the penstock, probably even of all station complex. Evidently the background stresses have tectonic nature.

The local stresses considerably differ from the background ones: they are concentrated on the place of the joint of the derivational tunnel and penstock and cover the baulk U-D, D-1, 1-2. Data of geodetic measurements are confirmed by hydrogeological observations. Exactly on this place we can observe abrupt fluctuations of subterranean waters. This can be evidently explained by leakage of the tunnel and enrichment of subterranean waters with percolating water. Local stresses can considerably affect the deformation of the derivational tunnel and the penstock [Ostrovskyi et al, 1993; Tretyak and Sidorov, 1994; Demedyuk et al, 1993].

Lets calculate allowable loads that correspond to limit of penstock elasticity to make conclusions about real danger of accumulation of the local deformational stresses.

$$P = hE\sqrt{3(1-v)^2 R}\ , \tag{1}$$

where:

v – Poisson coefficient,

E – Young modulus,

H – thickness of penstock wall;

R – pipe radius. For the steel v =0.25, and E = 2.06·10^5 MPa, assuming that h=0.02 m, and R=1.10 m, we can get P_{al} = 2230 MPa.

Using obtained values of absolute deformations we can calculate by Hooke's formula the maximum local stresses appeared during the period 05/1989 – 11/2007 on all baulks of the penstock:

$$P = \frac{E\Delta L}{L}, \tag{2}$$

where:

ΔL – absolute deformation;

L – baulk length. During period of observation the maximum values of the stresses were the following: $P_{D-1} = 930$ MPa ; $P_{1-2} = 66$ MPa ; $P_{2-3} = 41$ MPa ; $P_{3-4} = 49$ MPa .

During period 1992-1998, an inverse interrelation between water level in the storage reservoir and deformation accumulation is observed (fig. 5). Increasing of water level causes to stress relieving on the joints of the tunnels. It within certain limits confirms an important role of hydrodynamic stresses of TRHPS in the deformational processes of adjacent territories and, certainly, in the tectonic activity of Rikskyy break. It also confirms by the local earthquake of 1957 with magnitude 3-4 and epicenter in the village of Nyzhniy Bystryy (territory of station complex) as it coincides with time of filling the Tereblya storage reservoir.

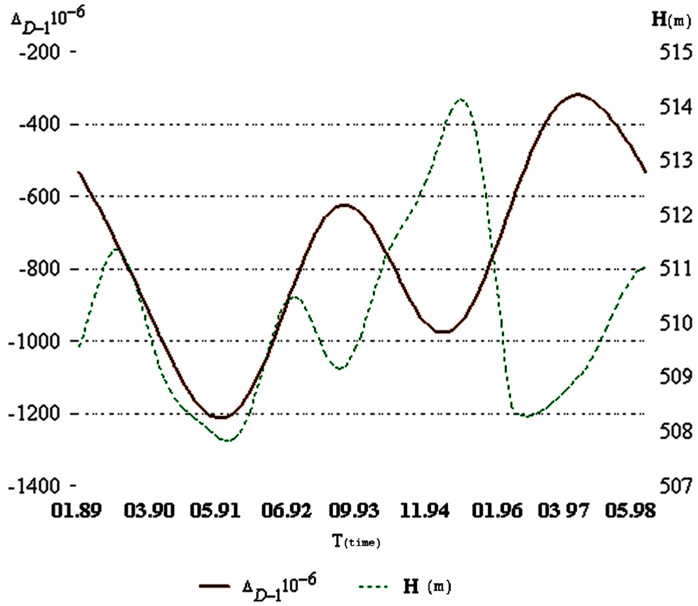


Figure 5. Simultaneous change of water level in Tereblya storage reservoir and accumulation of deformations on the joint of penstock and derivational tunnel

PARTS OF GENERAL PROBLEM NOT SOLVED BEFORE

It should be noted that determination of local deformations and stresses of the penstock using optical range and GPS measurements was being undertaken with three-month periodicity. Therefore, the determined dependence between water level in the storage reservoir and deformations of penstock baulks is sufficiently smoothed in time and does not reflect short-term deformations of the penstock (these deformations can appear when abrupt change of water level). When intensive precipitation occurs then water level in the storage reservoir can go up on 10-15 m during several days. In the time of planned investigations of derivational tunnel, the water level in the storage reservoir during 1-2 weeks is artificially decreasing to the minimum. In such cases deformations and stresses of the penstock can have totally different values and character of changes. Investigation of such processes is practically impossible when using spatial network of optical range and GPS measurements. To implement shot-term measurements (in several tens minutes), it is necessary to use four optical range finders on this network and to have four reflectors on each determined point. Technically this complicates work implementation very much. Application of GPS-receivers under conditions of satellite-restricted visibility requires long sessions (up to 10-12 hours) and this excludes possibility of short-term measurements.

TASK STATEMENT

For researching short-term deformations and stresses of the penstock application of electronic tacheometer Leica TPS 1201 was planned. It is a robotic tacheometer enabling to implement high precision short-term angular and linear measurements. Precision of measurements of horizontal and vertical angles is 1″. Tacheometer without reflector can measure distances less than 1 km. Tacheometer with one-prism reflector can measure distances up to 3.50 km, and with application of three prisms - up to 5.4 km with precision 1mm + 1.5 ppm. Additionally, it supports geodetic monitoring systems that enables in automatic mode in certain period to implement repeated measurements of control points. The device is equipped with sensor enabling in automatic mode to find reflector and make precise pointing on it without human assistance.

PRESENTATION OF MAIN MATERIAL

It is planned to implement the measurements using the tacheometer from one station T, located on the roof of the HPS control room (Fig. 1), on the four anchor supports with reflectors established on them. Measurements are not undertaken on points *U* and *D*. Point *U* is out of boundary of direct visibility from point *T*, and point *D* is destroyed in result of some repair-and-renewal operations. In such way short-term deformations of baulks 1-2, 2-3, and 3-4 were measured.

For *a priori* evaluation of precision of height measurement of point located on the anchor, support we used the following expression:

$$m_h = \sqrt{S^2 \cdot \cos^2 \alpha \frac{m_\beta^{\;2}}{\rho^2} + \sin^2 \alpha \cdot m_s^{\;2}} \;, \tag{3}$$

where:

S – measured tilt distance;

α – measured vertical angle; mean square error of vertical and horizontal circles measurement $m_\beta = 1''$, mean square error of distance measurement $m_s = 1_{mm} + 1.5_{mm} \cdot S_{(km)}$.

Mean square error of measuring coordinates *X* and *Y* (axis *Y* is at the intersection of the horizontal plane and vertical plane passing via point *T* and via point on the anchor support, axis *X* is perpendicular to axis *Y*) is determined using formulas:

$$m_x = S \cdot \cos\alpha \cdot \frac{m_\beta}{\rho} \tag{4}$$

$$m_y = m_s \cdot \cos\alpha \tag{5}$$

Mean square error of determination of point coordinates:

$$m = \sqrt{m^2{}_x + m^2{}_y + m^2{}_h} \tag{6}$$

Mean square error of measurement of distance between two points located between anchor supports *i, j*:

$$m_L = \sqrt{m_i^2 + m_j^2} \tag{7}$$

Mean square error of determination of baulk between two points:

$$m_D = \frac{m_L}{L} \tag{8}$$

where:

L – length of penstock baulk.

Mean square error of determination of deformation of baulk *i, j*:

$$m_p = E \cdot m_D \tag{9}$$

Calculated values of mean square errors are shown in Table 1.

Table 1. Mean square errors of determination of coordinates of anchor support points on the penstock

Point names	m_h (mm)	m_x (mm)	m_y (mm)	m (mm)
1	1.5	1.4	1.4	2.4
2	1.1	1.0	1.2	1.9
3	0.6	0.5	1.1	1.4
4	0.3	0.2	1.1	1.1

We can see from Table 2 that mean square errors of stresses are several times less than stresses values obtained using methods of spatial trilateration and GPS method. Evidently that application of tacheometer Leica TPS 1201 is sufficiently suitable for researching short-term deformations and stresses of the penstock.

Table 2. Mean square errors of determination of lengths, deformations and stresses of baulks on the penstock

Names of baulks	m_L (mm)	m_D *10^5	m_p (MPa)
1-2	3.1	3.37	7.0
2-3	2.3	2.30	4.8
3-4	1.7	2.52	5.2

For comparison lets determine mean square errors of elevations between points 1-2, 2-3, 3-4 applying the method of geometric leveling of *I* and *II* classes and robotic tacheometer. Obtained results are shown in Table 3. Analyzing the results we can assert that application of tacheometer Leica TPS 1201when determination of elevations on the lines with length under 400 m can completely replace the leveling of *I* class.

For researching short-term stresses of penstock during four days (06.11–10.11.2007) the twenty-four-hour measurements have been implemented.

Table 3. Mean square errors of determination of elevations between anchor supports of the penstock using geometric leveling of I and II classes and electronic tacheometer Leica TPS 1201

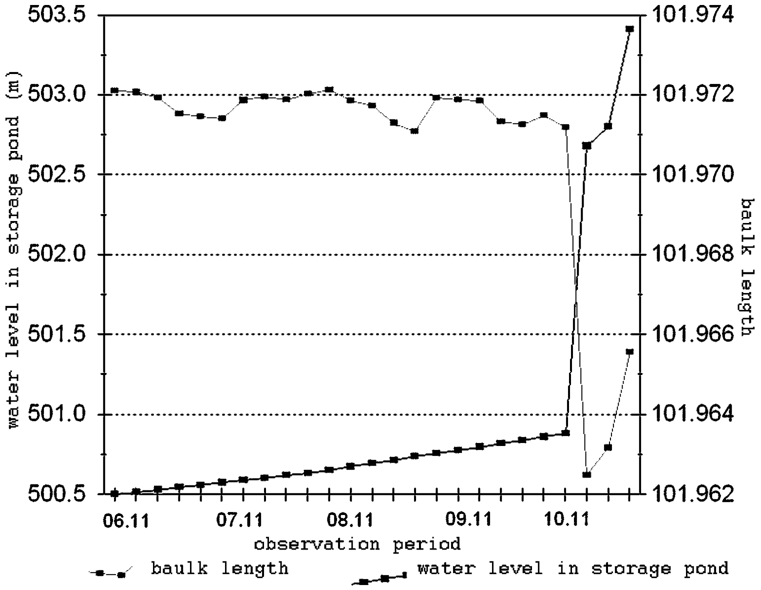
Names of baulks	Elevations between points (m)	Mean-square error determination elevations (mm)		
		Geometric levelling *I cl.*	Geometric levelling *II cl.*	Electronic tacheometer Leica TPS 1201
1-2	48.46	1.8	2.4	1.8
2-3	73.25	2.1	2.8	1.2
3-4	32.63	1.4	1.8	0.6

In these days the storage reservoir was being filled up after recurrent planned investigation of the derivational tunnel. Water level in the storage reservoir during this period changed from 500.5 m to 503.52 m.

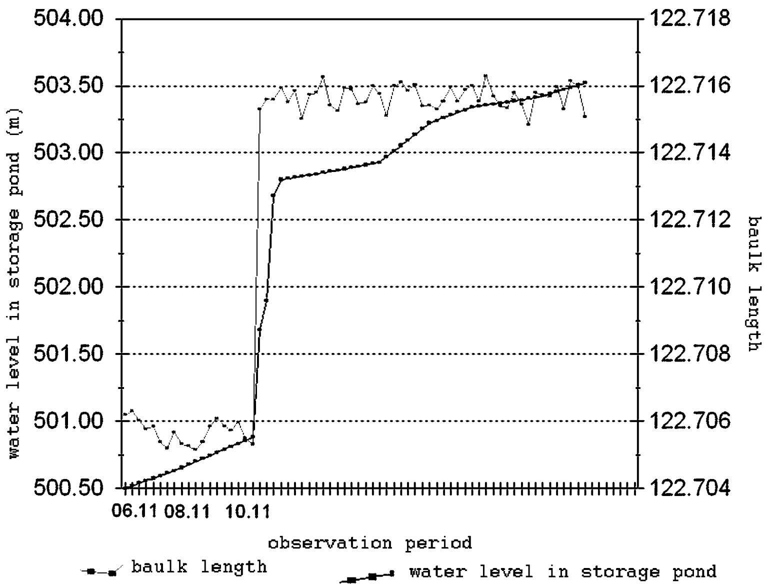
Measurements were undertaken with period 0.5 hour in automatic mode with sequential pointing on the reflectors 1-4. There were implemented 135 stages of linear and angular measurements on each reflector. Total number of measurements was 1087. Temperature of air was about 2˚C, atmospheric pressure – 725 mm of mercury column. Corrections on temperature and pressure were input into the tacheometer before beginning of observations and then automatically were included in the measurement results.

The work of the tacheometer was not strictly periodical as tight fog very often stopped the measurement process.

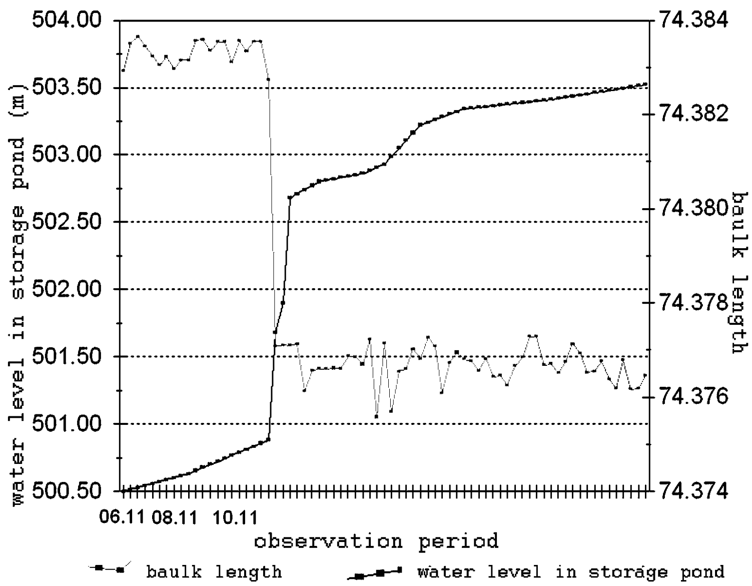
The results of measurements of lengths and elevations of the baulks and changing of water level in the storage reservoir during observation period are shown on fig. 6.



a) baulk 1-2



b) baulk 2-3



c) baulk 3-4

Figure 6. Dependence of change of the lengths of penstock baulks of Tereblya-Rikska HPS from the height of water level in the Tereblya storage reservoir

Direct dependence between change of lengths of all baulks of the penstock and change of water level in the storage reservoir is displayed on the fig. 6. Increasing of water level of 3 meters causes decreasing the length of the baulks 1-2 and 3-4 correspondently of 9 and 6 mm, and to increasing of length of the baulk 2-3 on 10 mm. It causes to appearance of stress (compression) in the baulk 1-2 : –18.2±7.0MPa, (tension) in the baulk 2-3 : +16.8±4.2 MPa, (compression) in the baulk 3-4: +16.6±5.2 MPa. Obviously the anchor support №2 was displaced in the direction of the support №1 when filling up the storage reservoir and this leaded to the compression of the baulk 1-2 and tension of the baulk 2-3.

One of the reason of anchor supports displacements and appearance of short-term stresses in the baulks of the penstock is increased saturation of the Rikskyy slope by waters when filling up the storage reservoir. This is confirmed by abrupt discharge of the slope sources when draining the storage reservoir. Increasing the kinematic activity of tectonic blocks of the Rikskyy break when filling up the storage reservoir can also be a possible reason of stresses appearance. During that time the moistening of joints of tectonic blocks is increasing and affects decreasing the friction between them and causes appearance of their displacements. If we assume that a change of water level in the storage reservoir in direct proportion causes to increase stresses in the penstock baulks then we can calculate the limits of these stresses. Measurement results show that filling up the storage reservoir of 1 meter leads to increasing the stresses in the penstock baulks of up to 5-6 MPa. Therefore, when maximum change of water level in the storage reservoir of 20 m happens, the change of stresses in the baulks can achieve 100-120 MPa. However, it should be noted that in this case the abrupt increase of water volume in the storage reservoir was not considered.

Appearance of short-term deformations and stresses of the penstock causes its displacements on the Rikskyy slope, creates some danger and requires systematic control.

For complete research of deformational processes in the body of the penstock it is necessary to implement permanent monitoring or systematic measurements of the baulk lengths with application of electronic tacheometer and integration of these observation with GPS measurements.

CONCLUSIONS

1. Analysis of geodetic works implemented on the geodynamic polygons of HPS built in different regions allows to assert that change of water level in artificial storage reservoirs generates local deformational anomalies of the earth surface, increases tectonic activity and sometimes can lead to abovementioned seismicity. Geodetic support of HPS functioning is an integral part of geodynamic monitoring of the surrounding territory.

2. According to the results of many-year optical range and GPS measurements undertaken on the spatial network of Tereblya-Rikska HPS it is established long-term dependences of change of deformations and stresses in the penstock.

3. Using a Leica TPS 1201 robotic electronic tacheometer during several days the monitoring of short-term stresses and deformations of the penstock baulks was implemented for researching these processes. The direct dependence of change of lengths of all baulks of the penstock from relatively abrupt change of water level in the storage reservoir was determined using the results of measurements. When a change of water level occurs, the short-term stresses in the penstock baulks are within the limits of 18 MPa and precision of their determination is ±7 MPa.

4. One of the reasons of anchor supports displacements and appearance of short-term stresses in the baulks of the penstock is the increased saturation of the Rikskyy slope by waters when filling up the storage reservoir. It is confirmed by abrupt discharge of the slope sources when draining the storage reservoir. Increasing kinematic activity of tectonic blocks of the Rikskyy break when filling up the storage reservoir can also be a possible reason of stresses appearance. The moistening of the joints of tectonic blocks is increasing and it affects decreasing the friction between them and results in appearance of their displacements. The appearance of short-term deformations and stresses of the penstock causes its

displacements on the Rikskyy slope and strongly affects the stability of engineering constructions, so it creates some danger and requires systematic control.

5. For complete research of deformational processes in the body of the penstock it is necessary to implement permanent monitoring or systematic measurements of the baulk lengths with application of electronic tacheometer and integration of these observations with GPS measurements.

6. The results of optical range and GPS measurements allows to determine long-term deformations and stresses of the penstock; the application of the proposed method was undertaken and shown the results of determination of deformational parameters of the penstock. Using the results of many-year observations, an anomalous distribution of deformational parameters in the body of the penstock was found. It was stipulated by the activity of the Rikskyy tectonic break and fluctuation of water level in the Tereblya storage reservoir. The proposed methodology of geodetic monitoring of penstocks is a reliable method of determination of deformational parameters and stresses of engineering constructions.

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