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ESTABLISHMENT OF THE AUTOMATED SYSTEM OF GEODETIC MONITORING FOR STRUCTURES OF TEREBLE-RITSKA HPP

The article presents the aspects of historical development of monitoring of Tereble-Ritska hydroelectric power station (HPP), which led to the need of establishing an automated system of geodetic monitoring (ASGM) of deformations of the water pipeline and other structures. Since 2018, the system has been automated and the instrumental part continues to be expanded. Thus, as of 2022, the instrumental part of ASGM includes 3 main components, namely: linear-angular measurements with the determination of meteorological parameters, satellite GNSS measurements, and piezometric measurements. This article presents the results of ASGM work in order to monitor deformations. There are also some advantages of using ASGM in comparison with classical measurements, which first of all allow determining of coordinates in real-time and increase the accuracy of spatial deformation detection to 2 mm (horizontal) and 3 mm (height) on an area of 2 km^2. It is also possible to inform the maintenance services of the monitored object when the received deformation exceeds the established limits. According to the results of the time series of linear-angular measurements, it can be stated that the pipeline undergoes seasonal displacements which are manifested in the horizontal displacement of supports towards the HPP building from winter to summer, and vice versa from summer to winter. To date, the amount of special data for the aggregate analysis of linear-angular measurements with the determination of meteorological parameters, GNSS measurements and piezometric measurements is insufficient. As data accumulates, it will be important to establish relationships between these parameters.

Key words: automated system of geodetic monitoring, deformation monitoring, linear-angular measurements, GNSS, piezometer, Tereble-Ritska HPP.

Introduction

The construction of hydroelectric power plants (HPPs) is an active intervention in the geological-tectonic, geodynamic and hydrological conditions of the region, which is also accompanied by large movements of water masses. This can lead to the intensification of deformation processes of engineering structures and, as a consequence death, accidents, destruction and material damage, which is especially important due to the significant operation time of HPPs in Ukraine [Tretyak et al., 2017; Farenyuk et al., 2020].

There are special systems for monitoring the displacement of dams, reservoirs and other structures of HPPs in Ukraine, some of which are partially or fully automated [Bisovetskyi et al., 2011; Tretyak et al., 2017]. Such systems include GNSS receivers, robotic electronic total stations, precision inclinometers, meteorological sensors, telecommunications equipment, etc. For such structural monitoring systems real-time as well as post-processed displacements are under consideration. There are plenty of studies on the HPPs on the Dnipro River, such as the stability of engineering structures by the automated geodetic monitoring system of Kaniv HPP [Tretyak et al., 2014], seasonal deformations of the Dnipro HPP dam based on GNSS measurements [Tretyak and Palyanytsia, 2021] control over the operation of installed automated monitoring systems [Bysovetsky et al., 2011; Tretyak et al., 2017].

Dnister Hydro Power Complex is under continuous monitoring: GNSS observation network is differentiated [Savchyn and Vaskovets, 2018], the relationship between construction stages and seismicity of the region is determined [Savchyn and Pronyshyn, 2020], kinematics of HPP-No. 1 dam are differentiated [Tretyak et al., 2021b] and the interrelation of altitude displacements of the GNSS sites due to non-tidal atmospheric loads are identified [Tretyak et al., 2021a]. A complex approach to data processing in a common centre for the preservation and visualization of the results of the Dnipro, Dnister, Middle Dnipro, and Kaniv HPPs has also been implemented [Tretyak et al., 2017].

The deformation monitoring system of the above-mentioned HPPs is always an individual solution for each station, taking into account the specific structural features of the object and the engineering and geological conditions of the region. A number of studies over the last decade only confirm the relevance of monitoring. At the same time, it is important to implement a fully automated system of geodetic monitoring (ASGM).

ASGM consists of three parts [Behr, et al., 1998; Barzaghi, et al., 2018; Mogylnyi et al., 2010; Zayats, et al., 2021]:

1. Instrumental.
2. Communication facilities.
3. Software.

The instrumental part includes a high-precision geodetic control network consisting of benchmarks that are periodically monitored by special geodetic equipment, such as GNNS receivers, electronic total stations, reflectors, incliometers, digital levels, meteorological sensors and other geotechnical sensors.

Communication facilities include switches, interfaces for downloading real-time information from the instrumental part of ASGM and its transfer to a server for further processing and interpretation.

Software consists of the following subsystems: sensor data collection, data processing, analysis and reporting. The main purpose of the software part of ASGM is the collection and combined processing of all available measurements in order to detect deformations. Also, this system automatically informs the responsible persons when some of the controlled parameters exceed the set threshold values.

This article is devoted to the features of ASGM monitoring of Tereble-Ritskaya HPP pressure pipeline, the main purpose of which is to determine the coordinates in real-time, improve the accuracy of measurements and the ability to inform the HPP maintenance service about potential damage.

Preliminary studies of Tereble-Ritska HPP

Tereble-Ritska HPP is a unique derivation-type hydroelectric power plant located in Khust district of Zakarpattia region (Ukraine). It is part of a powerful energy complex, so-called “Burschtynskyi Island”, which operates in the Zakarpattia, Lviv and Ivano-Frankivsk regions. HPP`s capacity is 27 MW. Annual electricity production, depending on the water level in rivers, on average is 123 million kWh. After the construction of the dam, the Vilshansk Reservoir with a volume of 23.7 million m³ and the area of the water mirror is 1.6 km² was created.

Fig. 1 shows a general view of Tereble-Ritska HPP on aerial photography and photos of the water pipeline.

Fig. 1. General view of Tereble-Ritska HPP on aerial photography and photos of water pipeline

The construction of the HPP in 1949–1955 used the features of its location, such as Tereblya River and Rika River flow at a distance of 4 km from each other, but the Tereblya River flows 200 m above the River. The special derivation tunnel 3.7 km long has been built between the rivers, which discharges the waters of the Tereblya River into the Rika River basin through HPP. This solution requires a special approach for both monitorings of spatial displacements of Tereble-Ritska HPP facilities and its automation.

Tereble-Ritska HPP was put into operation in 1956. Geodetic observations of the displacement of the water pipeline have been carried out since 1958

[Demedyuk et al., 1993]. Until 1989, the technique used allowed to perform only horizontal displacements of the water pipeline. To determine the complex deformations of the Tereble-Ritska HPP pressure pipeline in 1989, a special spatial geodetic network was created (Fig. 2).

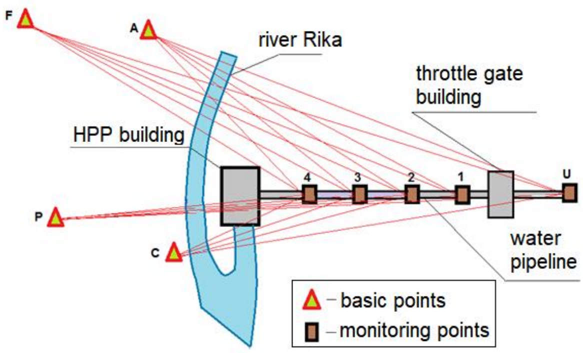


Fig. 2. Scheme of the spatial network of trilateration of Tereble-Ritska HPP [Demedyuk et al., 1993; Tretyak, et al., 2010]

Determination of deformations was performed by the trilateration method, but starting from the 45-cycle (05.2000) monitoring was performed by the method of satellite geodesy using GNSS measurements. For the period from 05.1989 to 08.2017, 67 cycles of observations were performed. Measurements were performed with GNSS receivers Leica SR-1200, TrimbleR7 in static mode and precision electronic total station TCRP 1201 (Leica).

To estimate the deformations, the components g_x, g_y, g_h, g – relative displacements along the X, Y, H axes and total displacement and Δ-dilatation (compression or tension) were used [Grytsyuk, 2010; Tretyak, et al., 2010]. There are short-term deformations, which depend on fluctuations in the water level in the reservoir, and long-term deformations, which are a consequence of the former. The general shift of geodetic points on the water pipeline explained cyclic deformations (joint-tension) due to the partial filling of cracks with salts and carbonates that fall out of aqueous solution [Kulchytskyi 2009; Tretyak, et al., 2009]. The HPP zone is located at a distance of about 16–18 km northeast of the zone of seismically active Transcarpathian deep fault (sutura) and at a distance of about 28–30 km from the zone of its junction with the seismically active Oaş meridian fault of the Transcarpathian depression. According to the results of seismological studies in the west of the district (23.43 ± 0.03ºS) submeridional deep (with earthquakes up to 38–52 km) seismically active zone of contact of Alcapa and Tisia-Dacia terrains in the Carpathian region of Ukraine [Nazarevych et al., 2016]. Performing the assessment of deformations in the region in August 2017, it was found that on part D-1, which corresponds to the junction of the derivation tunnel and the pressure pipeline, the compression is. –18.9×10^{-4}, and the loading is –0.0047×10^{5} mPa, with a critical value of 0.0223×10^{5} mPa.

Due to the detected deformations, in order to ensure the stability of the water pipeline, there is a need to change the measurement scheme to provide a fully automated process and determination of structural deformations in the shortest possible time.

Purpose

The purpose of the study is to show the features of the implementation and advantages of water pipeline of Tereble-Ritska HPP over the old system, in particular the possibility of using different sensors, which with the accumulation of data will allow more efficient monitoring of the object and real-time results.

Automated system of geodetic monitoring of water pipeline

In September 2018, a fundamentally new ASGM of the Tereble-Ritska HPP water pipeline was created (Fig. 3). The reflectors of the new system have offset from the previous monitoring points, but the same pylons of the geodetic network of the water pipeline are monitored, which essentially show the same physical displacements for both the old and the new system. Conversion of new data to the pre-determined ones, if necessary, is carried out taking into account the offset between the centers of monitoring points respectively.

As of 2022, the instrumental part of ASGM includes 3 main components that are fully automated:

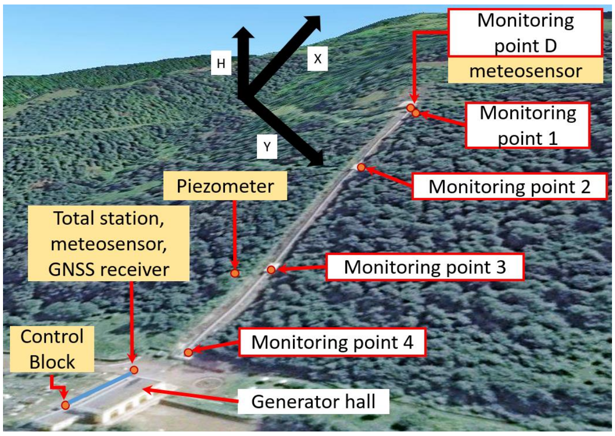
1. linear-angular measurements with the determination of meteorological parameters.
2. GNSS measurements.
3. piezometric measurements (change in surface water level).

The software was developed by the authors on the Lazarus platform and implemented on a Raspberry PI 3 microcomputer [Zayats et al., 2021]

· Analysis and filtering – special unit that reject measurements containing gross errors and outliers.

· Corrections for meteorological parameters – special subroutine that compute corrections to geodetic measurements for temperature, pressure and humidity of the atmosphere during the observation time.

· Combined adjustment – unified application that performs combined adjustment of GNSS and electronic total station observation and provides the accuracy estimation after adjustment



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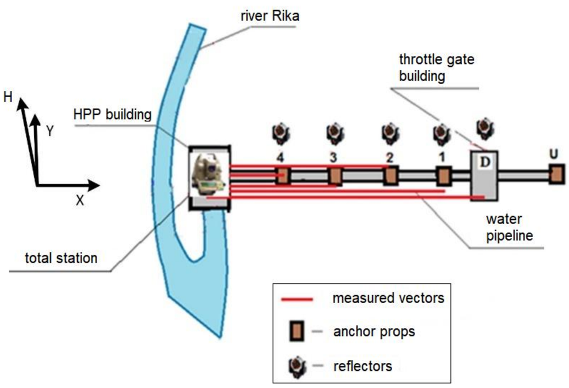

b

Fig. 3. Location of monitoring points of ASGM of Tereble-Ritska HPP water pipeline in the photo (a) and schematically (b) [Zayats, et al., 2021]

Linear-angular measurements

Fig. 4 shows a robotic total station LEICA TPS1000 installed on the roof of the generator hall. To minimize the impact on the environment, the total station is covered with special thermal and anti-vandal protection covered with insulating material.

Reflectors are installed on the anchor pillars and the throttle building. Fig. 5 shows the reflector fixed on the anchor pillar with special thermal and anti-vandal protection.

Fig. 4. Robotic total station LEICA TPS1000 with thermal protection installed on the roof of the generator hall

Fig. 5. Reflector with special thermal protection fixed on the anchor pillar

ASGM is connected to the Internet and transmits the results of repeated measurements to the server in real-time mode. The software installed on the server performs measurement processing and calculates the deformation parameters of the water pipeline. The frequency of repeated series of measurements is 6 hours. The Accuracy of measuring angles is 0.5–1", distances 2 mm. One series of measurements consists of six measurements of angles and distances to each reflector. In each series of all measurements for each reflector, the average of the vertical and horizontal directions, as well as the inclined distance, are calculated. Based on these results, the coordinates of all reflectors are determined for each series. The origin of the coordinate system is the centre of the total station.

In order to consider the optical refraction, two meteorological stations with a temperature gradient were installed directly next to the total station at the generator hall and at point D on the throttle gate building (Fig. 6).

Fig. 6. Meteorological stations with a temperature gradient installed on the generator hall (left) and on the throttle gate building (right)

The meteorological station-gradientometer with the BME280 sensor provides automated data collection of temperature gradient based on 2 meters in height, pressure and humidity.

Both measurements of the robotic total station and meteorological data are transferred to the central server of the Lviv Polytechnic in real-time mode. Specially designed software calculates the correction for measured angles and distances. After the corrections, linear-angular measurements are processed and the spatial coordinates of the reflectors and horizontal and vertical displacements are calculated for each epoch of measurements. The deformation parameters of the water pipeline are also determined.

The time series of displacements of X, Y, H components for points No. 1, 2, 3, 4, D are shown in Fig. 7. The location of the monitoring points and axes is shown in Fig. 3.

According to the results of the time series, it can be stated that the water pipeline undergoes seasonal displacements which are manifested in the horizontal displacement of pillars toward the HPP building from winter to summer, and vice versa are shifted towards the reservoir from summer to winter. Perpendicular to the body of the pipeline, the throttle gate building and anchor pillars No. 1, 2, 3 are shifted to the right from the pipeline from summer to winter, and the anchor pillar No. 4 is shifted to the left from the pipeline. From summer to winter anchor pillars change the direction of movement to the opposite. In altitude, almost all anchor pillars sink down in the summer and vice versa return to the starting position in the winter (see Figs. 1, 3).

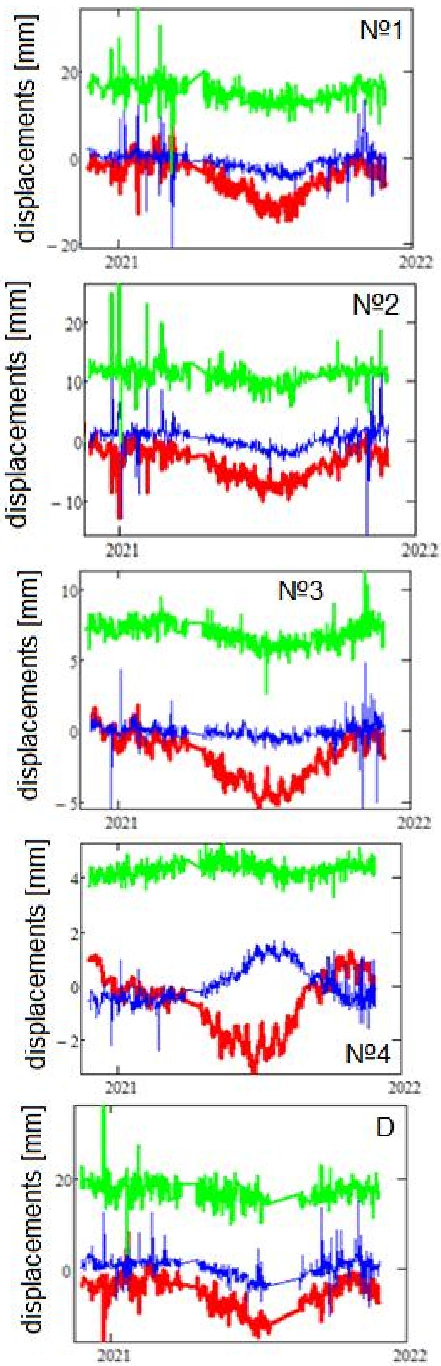

Fig. 7. Time series of displacements of X, Y, H components for points No, 1, 2, 3, 4, D (location and axes see in Fig. 3)

During these observation periods, the maximum deformation was recorded on part D-1 between the throttle gate building and monitoring point No. 1. For the period from November 2020 to October 2021, the maximum compression of the pipeline on this part reaches -16.5×10^{-4}. This indicates that extreme stresses increase significantly over time. In addition, it was found that in the summer of May-June 2021, all parts of the water pipeline in the range of -10×10^{-5} were slightly compressed, while at the same time on the part D-No. 1 compression was absent. Seasonal fluctuations of deformations were recorded on this part, but during the whole period of observations, the compression of this part increases in time, which indicates tectonic loads and changes in the hydrogeological state of the Rika slope. Since the length of the part is almost 10 m, the maximum compression of the run for the entire observation period is almost 16 mm. The average rate of its maximum growth is 0.6 mm/year. The load due to deformation for the entire 30-year period of observations is -0.0087×10^5 mPa, with a critical value of 0.0223×10^5 mPa.

Satellite GNSS measurements

In order to control the linear-angular measurements and supplement the monitoring network on the roof of the generator hall, a continuous GNSS station TERE was installed. The station is included in the Geoterrace network. It is located at a distance of about 20 meters from the total station. The station is equipped with a Trimble antenna and Novatel OEM-V3 receiver. The data transfer to the server, where the data of linear-angular measurements are stored, is configured. The use of satellite GNSS measurements for monitoring is widely used [Tretyak et al., 2017; Sokoła-Szewioła and Siejka, 2021].

The station was installed in 2021. Fig. 8 shows its general view. Fig. 9 shows the time series of the altitude components of the GNSS station. The GNSS station is included as the monitoring point with spatial reflector by total station.

Measurments of surface water level changes

Special boreholes were drilled in different parts of the slope during the construction of the Tereble-Ritska HPP. Measuring the level of surface water change was carried out mechanically and a few days regularly. It has been established that the surface water level correlates with displacements on the surface, in particular, according to GNSS measurements [Munekane, 2004]. Since the height difference between the rivers Tereblya and Rika is near 200 m, the groundwater level will differ in different parts of the slope. It is important to determine the changes in groundwater levels because the changes cause deformations on the surface. It is also important to perform such monitoring in real-time mode and with sufficient accuracy.

Fig. 8. Continuous GNSS station TERE
1 – GNSS antenna, 2 – reflector

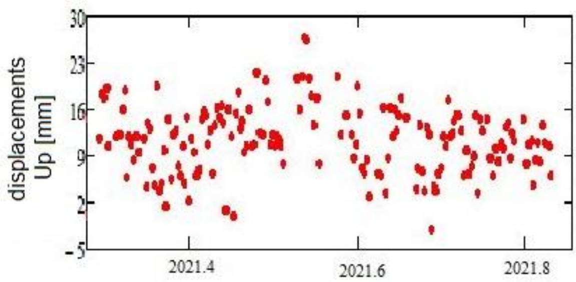

Fig. 9. Time series of the altitude component of the GNSS station

For this task, a piezometric sensor HDL300 was used, which is fixed in the borehole by the hardware part below the groundwater level (Fig. 10). Its constant power supply and data transfer to the server are established.

Fig. 10. Piezometer HDL300

Data processing allows getting a real-time graph of changes in groundwater levels. Fig. 11 shows the time series of changes in the groundwater level in the borehole. The peaks highlighted by the blue circles are related to the technical works of the descent-release of water at the station and are confirmed by the HPP`s staff.

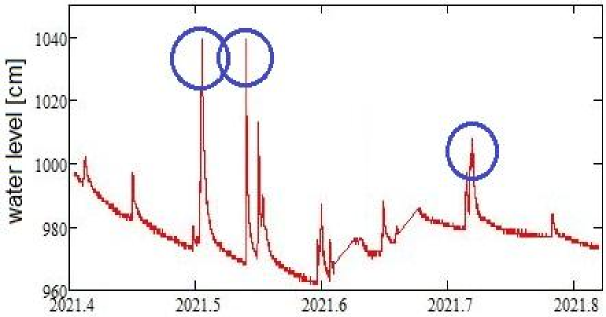

Fig. 11. Time series of changes in the groundwater level in the borehole

Comparing the time series of changes in the water level in the borehole and changes in the height of the GNSS station antenna, it is could be seen that lowering the water level corresponds to rising GNSS station and vice versa increase in water level is accompanied by subsidence of GNSS station. For the explanation of these changes, we need to accumulate a longer time series of measurement results.

Conclusions

Geodetic monitoring of displacements of anchor pillars of the Tereble-Ritska HPP water pipeline has been carried out since 1958. Initially, deformations were measured by trilateration methods, and since 2000 by GNSS. In recent decades, cycles of linear-angular measurements using high-precision total stations have been used. In order to increase the regularity of measurements, the system was automated in 2018.

Today ASGM includes 3 main components that are fully automated: linear-angular measurements with meteorological parameters, GNSS measurements, and measurements of changes in groundwater levels. The information is collected and transmitted via the Internet to the control centre at Lviv Polytechnic.

The advantages of the developed ASGM are:

- Reduced expenses on hardware based on its optimization.
- The ability to integrate into ASGM equipment from different manufacturers.
- Labor cost savings due to high system automation. Minimization of human interference in the system.
- Improving the accuracy of the results of geodetic measurements due to filtering and gross errors rejection and introducing corrections for meteorological parameters.
- Improving the accuracy of the detection of spatial deformations up to the level: 2 mm (in horizontal) and 3 mm (in height) on the area of 2 km^2 due to combined adjustment.
- Ability of the “real-time” coordinates determination.
- Ability to inform maintenance services of monitoring object when derived deformation overcomes established thresholds.

According to the results of the time series of linear-angular measurements, it can be stated that the water pipeline undergoes seasonal displacements which are manifested in the horizontal displacement of pillars toward the HPP building from winter to summer, and vice versa moving towards the reservoir from summer to winter.

To date, data are not sufficient for the aggregate analysis of linear-angular measurements with the determination of meteorological parameters, GNSS measurements and piezometric measurements. With the accumulation of a data array, it will be important to establish relationships between these parameters.

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СТВОРЕННЯ АВТОМАТИЗОВАНОЇ СИСТЕМИ МОНІТОРИНГУ СПОРУД ТЕРЕБЛЕ-РІЦЬКОЇ ГЕС

У статті показані аспекти історичного розвитку моніторингу Теребле-Ріцької ГЕС, які спричинили необхідність переходу до автоматизованої системи геодезичного моніторингу (АСГМ) деформацій напірного трубопроводу та інших споруд ГЕС. З 2018 року систему автоматизували та розширили її інструментальну частину. Так, станом на 2022 рік інструментальна частина АСГМ включає в себе три основні компоненти, а саме: лінійно-кутові виміри з визначенням метеорологічних параметрів, супутникові ГНСС-вимірювання, п'єзометричні вимірювання. У цій статті з метою моніторингу деформацій показані результати роботи АСГМ. Також наведені переваги застосування АСГМ у порівнянні з класичними вимірюваннями, які перш за все дають можливість постійного визначення координат в режимі реального часу з підвищенням точності виявлення просторових деформацій до рівня 2 мм (по горизонталі) і 3 мм (по висоті) на площі 2 км^2. Також передбачена можливість інформувати служби технічного обслуговування об'єкта моніторингу, коли отримана деформація перевищує встановлені пороги. За результатами часових серій лінійно-кутових вимірювань можна стверджувати, що напірний трубопровід зазнає сезонних зміщень, які проявляються у горизонтальному зміщенні опор в сторону будівлі ГЕС з зимового до літнього періоду, і навпаки, зміщуються в сторону водосховища з літнього періоду до зимового. На сьогодні для сукупного аналізу лінійно-кутових вимірів з визначенням метеорологічних параметрів, ГНСС-вимірювань та п'єзометричних вимірювань даних недостатньо. З накопиченням масиву даних важливим буде встановити взаємозв'язки між цими параметрами.

Ключові слова: автоматизована система моніторингу, моніторинг деформацій, лінійно-кутові вимірювання, ГНСС, п'єзометр, Теребле-Ріцька ГЕС.

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