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ORIGINAL PAPER

LOCAL GEODYNAMICS OF THE TERRITORY OF DNIESTER PUMPED STORAGE POWER PLANT

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ABSTRACT

The aim of the study is to identify the recent local geodynamic processes on the territory of the Dniester PSPP (Ukraine), which arose as a result of the additional man-caused load during the construction of hydro-technical structures. The research is based on the results of 17 cycles of periodic static GNSS campaigns conducted during 2004-2017. In this work the vectors of horizontal displacement of the reference GNSS network points of Dniester PSPP are determined and their scheme is constructed. On the basis of average vectors of horizontal movement velocities during 2004-2017, the value of the velocities of dilatation – the parameter of Earth surface deformation which characterises the relative area expansion or compression, is calculated. As a result of the analysis of velocity distribution of the dilatation of Dniester PSPP territory, the areas of extreme values of compression and stretching are revealed, which testify to the increased geodynamic activity of the pivot part, as well as the main structures of the construction.

INTRODUCTION

Seismically active regions, as well as areas that are under constant man-made load, require continuous local geodynamic monitoring. Recently, continuous (or periodic) GNSS measurements have been widely used for such monitoring which enables to determine the horizontal movements of points on coordinate axes. This approach is used to analyze the deformation processes in the northern part of Egypt (Mohamed et al., 2016). Using the results of satellite measurements at 13 GNSS points during 2012–2014, the velocity of horizontal movements, which fluctuate within 2–4 $^{mm}/_{year}$, is calculated. It is established that the main movement is in the NE direction. In (Khazaradze et al., 2014) the study of deformation processes in the Iberian Peninsula and northern Morocco is presented. On the basis of satellite measurements at 107 GNSS points during 1997–2011, velocities of horizontal movements, which fluctuate within 2–5 $^{mm}/_{year}$, are calculated. The obtained results confirmed previous studies: (Khazaradze et al., 2013), conducted at 15 GNSS points for the eastern part of Baetica (province in Spain); (Costantino and Angelini, 2011), conducted at 36 GNSS points for the region of Bages, Catalonia (Spain); (Gil et al., 2008), conducted at 5 GNSS points for Atlas Mountains (Morocco) – where the velocity of horizontal movements is within 2 $^{mm}/_{year}$. In (Alinia et al., 2017), studies of the dynamics of lithospheric plates in eastern Ontario and western Quebec (Canada) during period 2008–2012 are presented. The determined velocities of horizontal movements were within 2 $^{mm}/_{year}$ and were obtained on the basis of the processing of satellite measurements at 14 GNSS points. A similar research was conducted for Hainan Island (China) during 2009–2014 (Hu et al., 2016). The results show that the horizontal movement is mainly along SEE direction relative to the Eurasian Plate. The velocities of horizontal movements are between 4 and 7 $^{mm}/_{year}$. For the Southern Patagonian Icefield the velocities of horizontal movements at 43 GNSS points during 1996–2012 were between 2–7 $^{mm}/_{year}$ (Richter et al., 2016). Studies conducted on the Victoria regional network (19 GNSS points) in southern Australia in 2004 confirmed the preliminary values of the velocities of the Australian tectonic plate horizontal movements fluctuating within a range of 68 $^{mm}/_{year}$ (Zhang et al., 2005). In (Makolski et al., 2003; Kontny et al., 2004) a network of 19 GNSS points was used to determine local geodynamic processes in the Polish part of Karkonosze Mts and in the Karkonosze Foreland in Western Sudetes. The analysis of vector lengths' differences between GNSS points has shown significant changes (greater than 5 $^{mm}/_{year}$) near water reservoirs and mining areas. In (Cacoń et al., 2010) the study of local geodynamic processes Stołowe Mts in Central Sudetes located on the border of the Czech Republic and Poland is presented. The velocities of horizontal movements fluctuating within 2 $^{mm}/_{year}$ at 8 GNSS points during 1993–2009 were calculated on the basis of satellite measurements.

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Most engineering and technical facilities in Ukraine are equipped with pylons for periodic GNSS measurements and further determination of their horizontal movements. The largest in Europe, Dniester PSPP (Pumped Storage Power Plant), situated in the foothills of the Carpathians on the right bank of the Dniester River, 8 km NE of Sokyriany in Chernivtsi region (48°30′49″N, 27°28′24″E), is not an exception. Based on periodic satellite measurements at the GNSS points evenly located on the territory of Dniester PSPP, it was found out that during 2005–2014 period the velocity of horizontal movements of the territory was within the range of 0.5–1.2 $^{\mathrm{mm}}/_{\mathrm{year}}$, while the main movement was in the western direction (Sidorov et al., 2015).

The construction of Dniester PSPP started in 1983, and today 3 of 7 generators are operational what the first stage of construction is. Sidorov et al. (2015) note that during Dniester PSPP construction there were quite serious man-made interferences in the formed natural structure, as well as in the processes that are going through it. The cycle of the station's operation also results in an additional man-caused load, as well as a change in the hydrodynamic regime (Sidorov et al., 2015). The reaction of an array to the technogenic interference is a significant increase in local seismic activity. By 2011, according to seismic monitoring data, on average 5–7 local earthquakes with a magnitude M+0.9–2.9 were recorded annually. At the end of October 2012, the number of registered earthquakes increased significantly and reached 36. At the end of 2013, there was a rise in seismic events and there were already 61 local earthquakes registered. The number of local earthquakes in 2014 has increased to 160. In the first half of 2015, there were 91 local earthquakes registered. The growth of the local seismic activity of the area continues even now.

The increasing frequency of seismic events indicates the redistribution of a strained-deformed component that is accompanied by deformation of rock strength. At the same time, a large number of recorded seismic events have zero depth indicating activation of exogenous processes (landslides, etc.). Such processes are quite logical and reflect the reaction of the array to technogenic interference (Sidorov et al., 2015).

GENERAL DESCRIPTION OF DNIESTER PSPP CONTROL GNSS NETWORK

In 2003 Dniester PSPP control GNSS network was created to support construction and observation of strains slopes near major hydropower plants. The initial network consisted of 15 points conventionally divided into a framework and a working network, which respectively included 7 and 8 points (Sidorov et al., 2015). The points of the frame network are laid in the rocks at a depth of more than 10 meters and the points of the working network – more than 3 meters. The geometric configuration of the framework points was adopted taking into account the geological structure of the territory and ability to use GNSS measurements. This network can be considered a local geodynamic landfill.

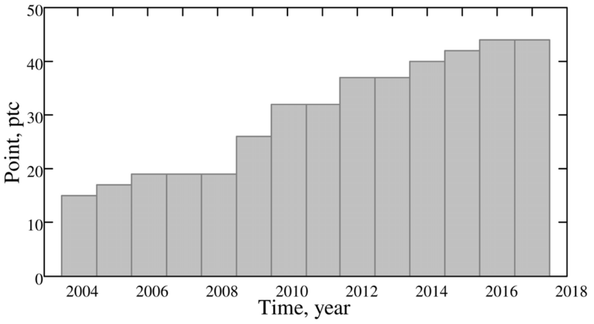

Fig. 1 Expanding and refining of Dniester PSPP control GNSS network.

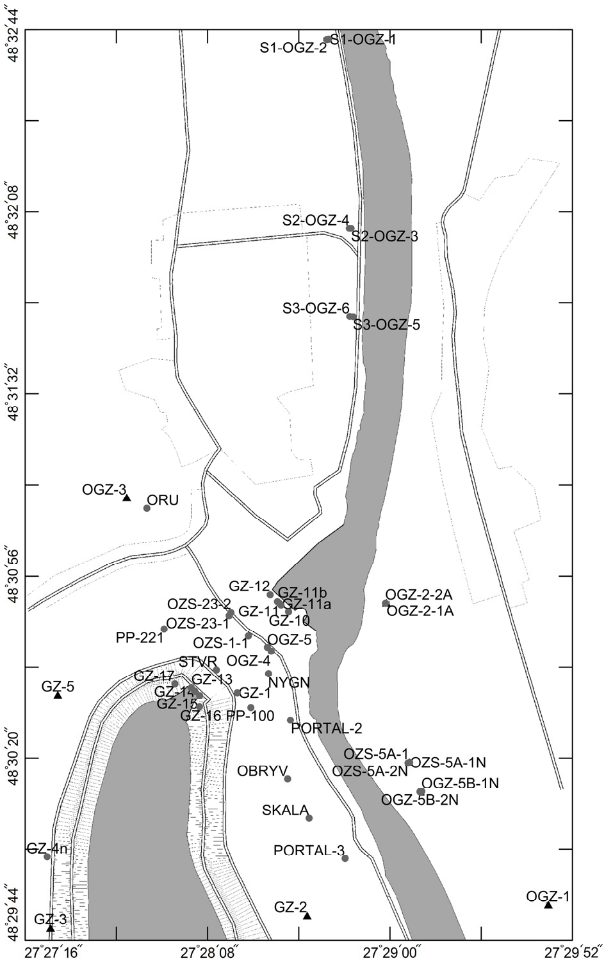

Fig. 2 Scheme of Dniester PSPP control GNSS network points in 2017 (▲– points of frame network; ●– points of working network).

Dniester PSPP control GNSS network was expanded and refined during the station construction (Fig. 1), so now there are 44 observation points within the studied area (Savchyn and Duma, 2016).

Dniester PSPP control GNSS network in 2017 is presented in Figure 2.

All points of Dniester PSPP control GNSS network provide for forced centring of GNSS receiver antennas, except for two (PP-100 and PP-221), where the centring must be performed with the help of an optical plummet.

The control GNSS network is extended northward along the Dniester and covers the area of approximately 10 km^2. The distance between the points is in the range of 5 to 4900 meters.

ANALYSIS OF THE RESULTS OF GNSS CAMPAIGNS

The periodic static satellite measurements (seasonal cycles) at points of Dniester PSPP control GNSS network have been carried out since 2004 (Sidorov et al., 2015). This methodology is considered to be a classical one in satellite measurements, which foresee simultaneous measuring between two or more fixed GNSS receivers. Duration of observations depends on the length of the measured baselines, the number of simultaneously visible satellites, types of receivers and the required accuracy. Bisovetskiy et al. (2011) note that this methodology is widely used to monitor a number of Ukrainian HPPs and PSPPs such as Kyiv PSPP (2003, 2004 and 2009); Kaniv HPP (2007 and 2010); Kremenchug HPP (2000, 2001 and 2007); Dniprodzerzhynsk HPP (2007); Dnipro HPP (1997, 2005 and 2010). It should be noted that for these objects during the period of observations the accuracy of the horizontal displacement was 2 mm, and vertical – 3 mm.

A special program for baseline measurement and session conducting has been developed for Dniester PSPP control GNSS network that optimizes the configuration of the receivers' location and minimizes transport costs (Tretyak and Sidorov, 2012). According to the developed program to reduce different GNSS receivers at each point of control GNSS network, 3 or 4 independent measurement sessions perform the systematic errors in each cycle. As a result, the total measuring time for each of the points in each cycle is about 18–24 hours. It should be taken into account that one cycle lasts for 10 measuring days and is carried out at the end of October/beginning of November every year. In addition, one additional measurement cycle was carried out in early May in 2004, 2005 and 2017.

The processing of satellite measurements is performed in Leica GeoOffice software with a data interval of 5 seconds and a cutoff angle 10°. The Hopfield model is used to take into account the influence of the troposphere. The ionosphere model is calculated in the Leica GeoOffice software based on the measurements. This is advantageous, as the model computed is in accordance with conditions prevalent at the time and position of observation.

Currently, 17 cycles of GNSS measurement have been carried out and processed, and coordinates have been obtained in each of them. On the basis of definite coordinates, the horizontal displacement of the points for each measurement cycle is calculated.

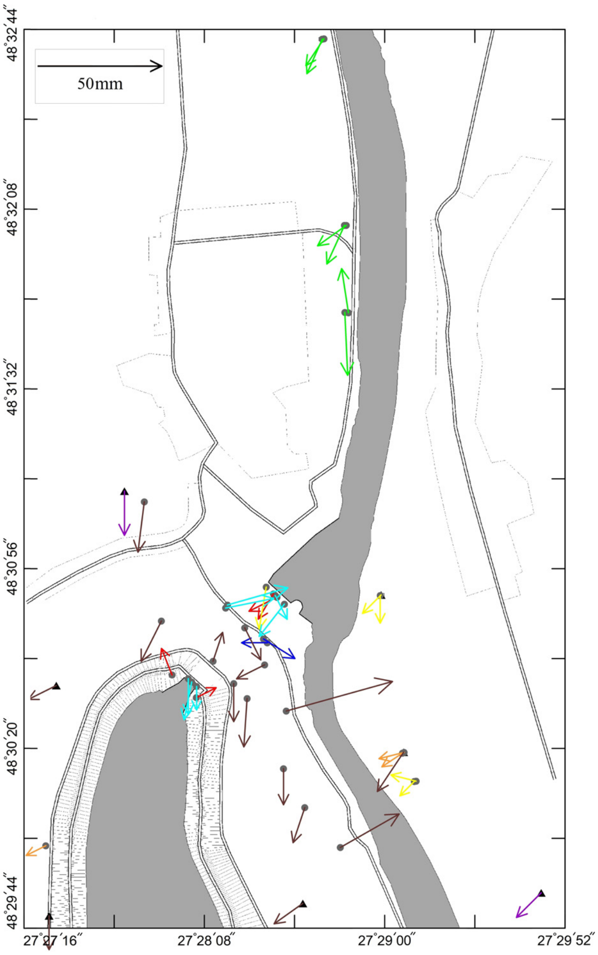

Fig. 3 The scheme of horizontal displacement of the points of Dniester PSPP control GNSS network during 2004–2017

(▲– points of frame network; ●– points of working network; → – 2–17 cycles; → – 3–17 cycles; →6–17 cycles; → – 9–17 cycles; → – 10–17 cycles; → – 12–17 cycles; → – 14–17 cycles; → – 15–17 cycles).

Figure 3 shows the scheme of horizontal displacement of the points of Dniester PSPP control GNSS network for the whole period of measurements (2004–2017).

The lengths of the determined vectors are within 2–44 mm that indicates different (uneven) velocity of the horizontal movements of the investigated area. The maximum horizontal displacement was observed in 2009, 2011 and 2013, and the minimum – in 2005, 2006 and 2007. It must be noted that in each measurement cycle a significant number of horizontal displacement vectors varies within the range of 0–2 mm, so it does not exceed the mean square error of their determination ±2 mm (Sidorov et al., 2015).

Vectors of horizontal displacement of the working network points (see Fig. 3**)** have different directions, but most of them indicate the S and SW direction of movement. The same direction of movement is observed at all points of the control network. The S and SW direction of movement of the points located around the upper reservoir is apparently due to the artificial loading of the territory by putting into operation the upper reservoir on the whole area to a mark of 220.5 meters with the volume of 19.3 million m^3 (October 26, 2012). The most intense horizontal displacement of different directions is recorded in the construction of the main buildings.

GEODYNAMIC INTERPRETATION OF THE RESULTS

The results of the GNSS campaigns were used to determine current local geodynamic processes on the territory of Dniester PSPP. In order to do this, the transition from the calculated vectors of horizontal displacements of the control GNSS network points to their average velocities for the period of 2004–2017 was made. The values of the calculated average velocities are rather small and are within the range of 0.4–4.6 $^{mm}/_{year}$. Only at 7 points, the average velocity is larger than 2 $^{mm}/_{year}$. The highest values of average velocities of 4.6 and 4.0 $^{mm}/_{year}$ are observed at points with a small period of measurements – 1.5.

Parameters of the Earth surface deformation are logically calculated for centres of elementary triangles (Tretyak and Vovk, 2014). Therefore, using the Delone triangulation the territory of Dniester PSPP is divided into a network of triangles with vertices at GNSS points. By means of linear interpolation, within the limits of each triangle the velocity of dilatation – the parameter of the Earth surface deformation which characterizes the relative expansion or compression of the area of the territory is calculated on three of its vertices (Sagiya et al., 2000; Kostiuk et al., 2010; Abdel-Monem et al., 2011; Mohamed et al., 2016):

$$\Delta = e_{xx} + e_{yy} \tag{1}$$

where e_{xx} and e_{yy} are components of the velocity tensor of Earth surface deformation.

These components can be determined as follows:

$$e_{xx} = \frac{1}{\Delta t} \cdot \frac{\partial u}{\partial x}$$
$$e_{yy} = \frac{1}{\Delta t} \cdot \frac{\partial v}{\partial y} \tag{2}$$

where (u , v) are the displacements at the point during the time interval Δt in the directions of (x , y).

The choice of this parameter is based on the analysis of previous studies performed on the Antarctic Peninsula (Tretyak and Golubinka, 2006), northern Tian Shan (Kostiuk et al., 2010), South-Eastern Europe (Marchenko et al., 2012), Europe (Tretyak and Vovk, 2014), northern part of Egypt (Mohamed et al., 2016) and others.

Using calculated values a map-diagram of the distribution of dilatation velocity of the territory of Dniester PSPP is constructed. It should be noted that in order to avoid distortion of the results all zones were considered to be stable if their values of the velocities of the Earth surface dilatation were within ±0.2 10^{-10}. This map also depicts the main fault zones of the seconds and the third orders obtained from (Sarnavski and Ovsiannikov, 2005) (see Fig. 4). In a tectonic way, the territory of Dniester PSPP is located on the outskirts of the SW part of the Eastern European platform within the bounds of Volyn-Podilsky and Moldavian plates with the projection of the Ukrainian shield which is cut off by the Podilsky fault zone (Sarnavski and Ovsiannikov, 2005). Thereby, the research area is complicated by transverse faults of the NE stretch and is considered as a series of low-amplitude faults that break the foundation into small blocks. The presented fault zones clearly correlate with the epicentres of registered local earthquakes. This confirms the assumption (Verbytskyi et al., 2005) about the possibility of creating new zones of local seismic activity since the research area is located in the zone where recent tectonic movements are changing.

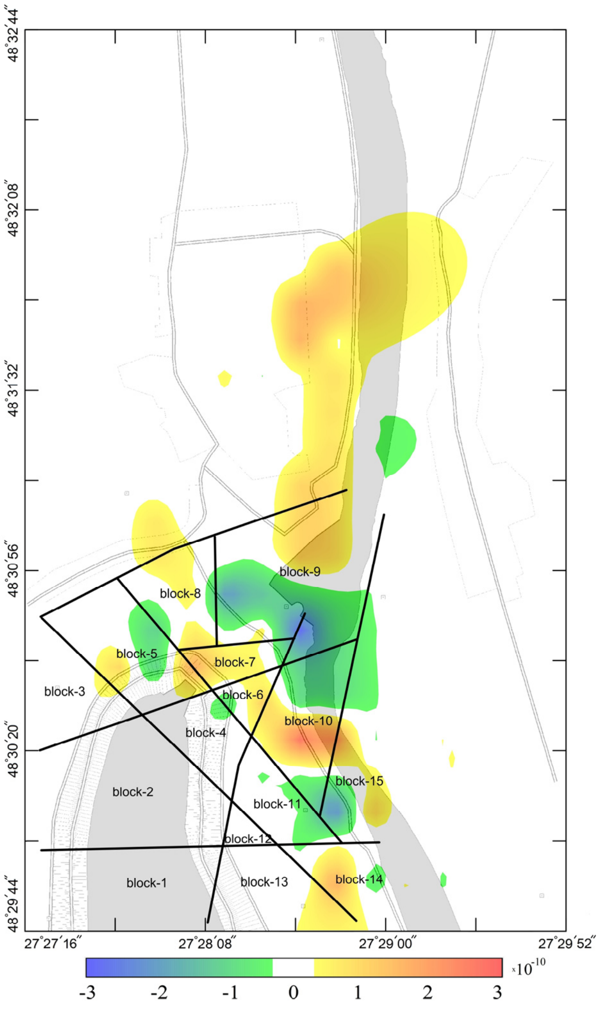

Fig. 4 The map-diagram of the distribution of dilatation velocity on the territory of Dniester PSPP for the period of 2004–2017

(▬– main fault zones of the second and third orders).

As a result of the analysis of the distribution of dilatation velocity on the territory of Dniester PSPP, the areas of extreme values of compression (more than $+2\cdot 10^{-10}$) and stretching (less than $-2\cdot 10^{-10}$) were detected that testify to the increased geodynamic activity of pivot part and the main structures of construction area. The increase in the compression level in blocks 6, 7, 10 and 14 was obviously caused by slope increase due to the filling of the upper reservoir. Confirmation may be lateral displacements of indigenous semi-skeletal rocks that arose during the filling of the upper reservoir (Sarnavski and Ovsiannikov, 2005). On the other hand, the increase in tensile strength in blocks 9 and 15 is due to the artificial unloading of the array by excavation of the soil in the excavation pit, underground mining and water pumping.

CONCLUSIONS AND DISCUSSION

The non-stationary (dynamic) operation of the hydrotechnical structures of Dniester PSPP, as well as the long period of their construction, have caused various (uneven) recent local horizontal movements within the investigated area.

The values of the calculated average velocities of the horizontal movements are rather small and are within the range of 0.4–4.6 $^{\mathrm{mm}}/_{\mathrm{year}}$. The average velocity is larger than 2 $^{\mathrm{mm}}/_{\mathrm{year}}$ only at 7 points.

The main geodynamic zones of extreme values of compression and stretching which arose as a result of additional man-made loading by the construction of hydraulic structures are highlighted.

It was established that the most active deformation processes are observed in the area of the main hydro technical structures of Dniester PSPP and are quite changing.

The presented results obtained on the basis of periodic static satellite measurements do not allow revealing short-term recent local deformation processes. Therefore, to detect and track such processes, as well as their interpretation, it is expedient to increase the frequency of measurement cycles. Moreover, for continuous monitoring and hazard assessment an automated deformation monitoring system should be deployed in the hydrometeorological district. Such a system will allow constant construction and operation monitoring of Dniester PSPP in order to provide conditions for its safe functioning to preserve people's lives, the environment and economic infrastructure.

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