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System of determination of horizontal displacements of pressure pipeline supports along the slope of the hill

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Abstract. For several years, the team of the Institute of Geodesy and Cartography, Warsaw, has been conducting monitoring of the safety of one of Polish hydraulic structures, namely Żarnowiec hydropower plant. In the face of construction disasters caused by landslides that has taken place in the world in recent years, the scope of the monitoring of the facility has been extended by testing the stability of reinforced concrete pressure pipeline supports located on the slope of the hill. This paper concerns the description of the method that has been developed for this purpose. It includes the design and construction of an innovative device that allows the use of existing vertical network benchmarks as points for measuring horizontal displacements. The design of the instrument, which allows setting the EDM prism on different types of survey benchmarks, has been described. Aspects of the selection of unusual shape of the special surveying control network have also been discussed. The method of processing the measurement results has been presented and the results of displacements of monitored sites were analysed.

Keywords: monitoring, landslides, displacements, pipeline supports

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1. Introduction

According to Szafarczyk and Puniach (2011) “Landslides are among the most common phenomena that cause natural disasters. Therefore, conducting monitoring of moving soil masses is necessary to ensure the safety of people and their property. There are many causes that trigger landslides, and then determine the rate of displacements of ground. They can be grouped according to a variety of assumptions. For example, the internal causes of mass movements include downcutting and lateral erosion of the slopes, tectonic movements and earthquakes, but rainwater or snowmelt saturation, and human activities are treated as external conditions adversely affecting the stability of slopes. Another method of grouping them includes passive factors (such as geology), active agents, that is all the processes occurring on the slope, and anthropogenic factors, such as mechanical undercutting of slopes, or loading slopes by development”.

Displacements of soil masses of landslides pose a particular threat to the stability and security of engineering objects and constructions situated on the slope. Monitoring of potentially moving soil masses is usually reduced to the determination of horizontal and vertical displacements of engineering objects and structures located on a slope.

More than thirty years ago Lazzarini (1977) already pointed out that “the most common structures that require periodic or even continuous monitoring of their condition are dams”.

Taking into account the above statements, as well as numerous construction disasters, especially increasing of their number in the last few years, the Department of Geodesy and Geodynamics of the Institute of Geodesy and Cartography, together with the Polska Grupa Energetyczna Energia Odnawialna SA, have decided to extend monitoring of Żarnowiec hydroelectric power plant facility by testing the stability of reinforced concrete pressure pipeline supports located on the slope of the hill. Until now, methods for monitoring landslides and horizontal displacements of objects located on them, consisted mainly of stabilizing special posts for instruments and controlled points, such as columns with forced centering, which required considerable funding. The method of monitoring the safety of an object in regard to horizontal displacements, by using already existing survey benchmarks, so far used to determine vertical displacements, is presented in this paper.

2. Description of the object and analysis of risks

Four pressure pipelines of 1100 m (936 m outdoors) each, running down the slope with elevation

Fig. 1. Aerial view of Żarnowiec hydropower plant (Brochure, 1998)

of 80 m, bring the water from the upper reservoir to the pumping turbine located several meters below the sea level (Fig. 1). The pipeline route is divided into segments, which are supported on fixed and mobile supports spaced approximately every 22 metres. On each support in its reinforced concrete part, four survey benchmarks, located at each of the support corners, are stabilized. Every year, the survey of vertical displacements of benchmarks installed on these supports is made. To acquire full information about a possible threat to the object, surveying monitoring was extended by measuring horizontal displacement of pressure pipeline supports.

The first stage involved conducting the analysis of changes in the length of the pipelines due to their physical properties. Assuming a coefficient of thermal expansion of steel equal to $\alpha = 12 \cdot 10^{-6}$/K, change in temperature of 20°C causes change the length of a single 22 m segment of the pipeline by 5 mm. Taking under consideration the spacing of supports every 22 m on average, it can be concluded that the change in length of this section of the pipeline by 200 mm may exceed the elastic limit of steel, while the change in length of 1500 mm can result in exceeding the limit of its tensile strength. This type of phenomenon may be particularly dangerous in case of increasing the distance between supports in winter, because then the thermal reduction of the length of the pipes and the decrease in strength of steel follows. Brittle fractures resulting from excessive stretching of the pipeline between supports may then occur (Ziółko, 1970). The occurrence of such a drastic value as the limit of elasticity is unlikely, but cannot be ruled out, especially taking into consideration unexpected landslides (over 1300) on the slopes in the regions of Śląsk and Małopolska in May – June 2010 due to heavy rainfall (Szafarczyk and Puniach, 2011). At this point, it must be mentioned that the moveable support structure (Fig. 2) allows some movement of the pipes on reinforced concrete footings, and pipeline expansion joints are located at fixed supports (Fig. 3) spaced approximately every 150 m. An important element of safety monitoring should therefore be detecting and identifying changes in the distance between consecutive supports of each pipeline, and determining dislocations of various supports, such as those caused by landslide tendencies on the slope surface on the pipeline route.

3. Concept of a special control network

In view of previously given values of the thermal change in length of pipe, approximate data of their

Fig. 2. Mobile supports

Fig. 3. Fixed supports

elastic limits and possible accuracy of precise measurements of length and angles, it has been estimated that the distances between marks on successive pipe supports should be determined with the standard uncertainty of less than 3 mm. Because the monitored facility lacks typical survey marks used for angular-linear measuring, a method was developed to determine the horizontal displacements of pipeline supports, using existing benchmarks.

Existing aiming directions, access to surveying marks and requirements in regard to precision of determining the horizontal displacement in the direction of the axis of pipelines were taken into account in developing the concept of determining the horizontal displacement of pipeline supports. Survey marks in the form of benchmarks are stabilized in each of the corners of the foundation being a part of the support of the pipeline. Pipes with diameters within the range 5.40 – 7.10 m have the average slope of 9%. The lower surface of pipe is at an average distance of 85 cm from the ground surface. Points to be analyzed are located roughly in a rectangle of dimensions 37 × 932 m. Parallel to the pipeline axis, there is an enclosed and unwooded zone about 10 m wide, counting from each of the margin pipelines. In view of the above considerations, a special extended surveying control network has been created, which enables high-precision determination of coordinates along the pipeline axis. The authors of this concept chose a measurement variant which is less onerous, faster, giving the results in an uniform coordinate system, however, suffers from an increased error in the determination of location of points for the component perpendicular to the pipeline axis. However, in this case, focusing attention on the displacements parallel to the axis of pipelines is the most important factor in detection of possible landslides at the examined object.

Diagram of the surveying control network shown in Figure 4.

4. Adapter

To enable the use of existing survey benchmarks, a novel device – an adapter, consisting of an EDM reflector with a target plate, a rod and a set of ends, was designed and built. It was necessary to create several ends, because the existing benchmarks which were installed in different periods vary in regard to the diameter of the pin, the head surface and the height of the sticking out part of the benchmark. The device allows for precise centering of the reflector over the different types of benchmarks.

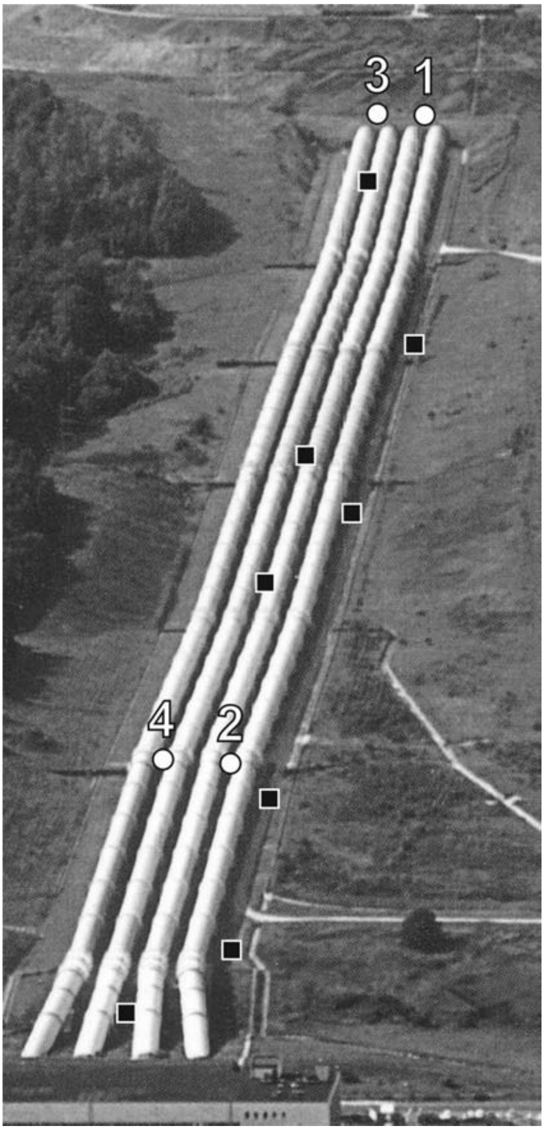

Fig. 4. Diagram of surveying control network (white circles – main instrument sites designed, black squares – auxiliary positions)

The diagram of the device is shown in Figure 5. The prism (1) and the target plate (2) are fixed on the coaxial cylinder (3) ending at the bottom in a conical hole (4) used to position it unambiguously on the front benchmark (5). The cylinder (3) is connected to the frame (6), which is attached to the sleeve (7) used to attach a standard vertical plumb rod (9) with a spherical level (8). The roller (3) and the coaxial plumb rod are set in a vertical position by using two standard supports with adjustable lengths. It can also be set manually, without the use of supports.

Prism and shield are mounted pivotally on the roller in order to allow for directing it perpendicularly to the direction of targeting through the total station: horizontally by rotating the roller (3) on the benchmark around its axis and in a vertical plane by rotating the mirror and the disc around the horizontal axis (10) connecting them with the frame (6).

Due to the different diameters of the individual front benchmarks and varied heights of their elements protruding above surfaces of the supports, if necessary, exchangeable conical ends of varying diameters and variable cone angles, bolted to the cylinder (3), should be used. These ends allow the setting of the cylinder (3) on a benchmark in such way, that the conical opening covers the benchmark head, and its edge is not resting on the concrete surface.

5. Baseline and Control Measurement of the Network

In order to carry out measurements, four main instrument sites were designed, which are marked in the diagram as white circles, and several auxiliary positions marked with black squares. Points 1 and 3 are located on the top of the retaining wall (above the top of the pipeline), and points 2 and 4 on the fixed supports at the bottom of the pipeline. They are situated approximately in the two axis between the inner and outer pipelines. Auxiliary sites were used to measure the few points not visible from the main sites, and to increase the stiffness of the surveying control network. All instrument positions were treated as free points because of the lack of their permanent stabilization. Due to the large size of fixed supports (Fig. 3), only a few benchmarks (approximately 10%) were seen from two major

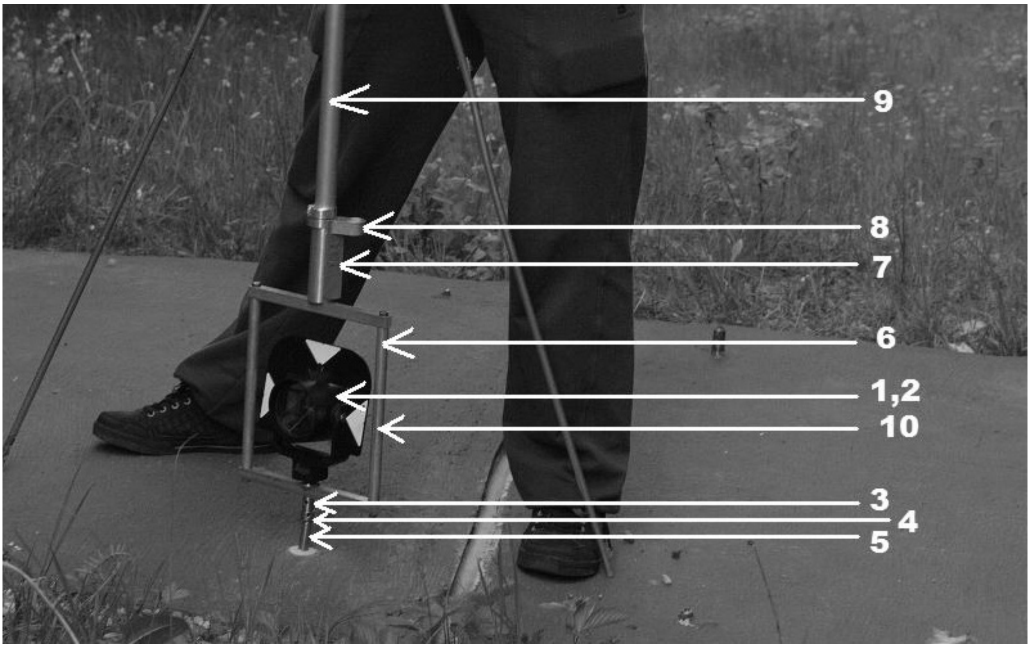

Fig. 5. Adapter for precise setting a prism on a survey benchmark

instrument sites of the surveying control network (from points 1 and 2 or from points 3 and 4). Supplementary sites of the surveying control network – approximately 15% of all benchmarks – allowed to make additional angular-linear observations.

To ensure two independent determinations of the position of each of the survey benchmarks, two separate angular-linear measurements of all control network were performed. The first measurement cycle, the so-called initial measurement, was conducted in 2011. Measurements were made with a proven Leica TC2002 precise total station, the EDM of which had been calibrated before 2011 measuring season. To determine the environmental conditions (temperature, humidity, pressure), approved Väisälä instruments were used. It was assumed that the measurements would be carried out according to the rules governing precise surveying measurements. Therefore, measurements were made at optimal, for distance measurements, atmospheric conditions (cloudy day, light wind). Measurements on sunny days were excluded, because the uneven insolation and associated heating up of the pipelines would cause significant air turbulence in the area, adversely affecting the accuracy of the measurement. In 2012 a control measurement of all angular-linear network was made with the same assumptions as in 2011.

6. Processing of observations

In order to adjust the observations taken in 2011, it was assumed that the origin of the coordinate system would be located in point 3, where the *Y*-axis was directed toward the point 4, and the *X*-axis was directed towards the point 1. The observations were adjusted applying free least squares adjustment, where the coordinates of the point 3 and the azimuth of the 3–4 side were accepted as known and error-free. The obtained standard uncertainty for the *Y* and *X* coordinates equaled $m_Y = 0.7$ mm, and $m_X = 23.4$ mm, respectively.

The same reference frame as well as the assumption of error-free point 3 coordinates and the 3–4 side azimuth were used in the least squares adjustment of the observations taken in 2012. The obtained standard uncertainty for the *Y* and *X* coordinates equalled $m_Y = 1.2$ mm, and $m_X = 32.3$ mm, respectively.

The effect of linking the surveying network to the surveying control on the accuracy of the results was widely discussed in the literature (e.g., Janusz, 1965). Since in the area of the object there are no sites that would serve as permanent reference points, it was assumed that the measurement sites would be considered as free stations. To determine the displacement of monitored sites, the results obtained in 2011 and 2012 were shown in a uniform coordinate system. For this purpose, an initial transformation based on the monitored points was performed, and then apparent horizontal displacement of survey benchmarks was determined. Isometric transformation was used to eliminate the scale error (Janusz, 2002). After discarding the points for which the displacements were the greatest, the final isometric transformation was made, which served as the basis for calculating the displacement of all benchmarks. Due to the lack of stable, yet durable reference benchmarks, final results were presented not only as a displacement of points dX, dY, but also as a displacement of dDY sections along the slope, determined by a pair of benchmarks nearest to each other. In this way a direct indication whether the adjacent supports came closer to one another, or moved away, was obtained.

Considering the standard uncertainty for consecutive least squares adjustments $m_{Y2011} = 0.7$ mm and $m_{Y2012} = 1.2$ mm, the standard uncertainty of displacements of points $m_{dy} = 1.4$ mm was determined using the law of error propagation. It follows that the standard uncertainty of section displacement determination was $m_{\mathrm{dD}Y} = 2.0$ mm, and its expanded value was $m_{\mathrm{dD}Y\,(k=2)} = 4.0$ mm. It was assumed that the displacement could be considered significant if its value was at least twice its standard uncertainty (Prószyński and Kwaśniak, 2006).

Average absolute values of displacement for components along the slope of the pressure pipeline routes were $|dY|_{\mathrm{mean}} = 1.7$ mm, while the average absolute values of displacement of sections determined by a pair of benchmarks nearest to each other along the slope of pressure pipeline route were $|\mathrm{dD}Y|_{\mathrm{mean}} = 0.8$ mm. These values, determined for the sections, were lower than the values determined for the Y component, because systematic measurement errors (mainly of environmental origin) were largely eliminated. Three cases where $|\mathrm{dD}Y|$ exceeded 4.0 mm were detected. After a detailed analysis of these cases it was found that the increased value for different sections was not due to their actual displacement, but due a centering error. Namely, the top surfaces of these benchmarks were damaged up to such extent that it was not possible to set the adapter precisely. In addition, an analysis of displacements $|\mathrm{dD}Y|$ exceeding 1.5 mm was performed. The concerned sections proved to be measured not only from one measuring station. The resulting differences were due not only to the propagation of least squares adjustment errors of the network, but also errors in determining the atmospheric refraction coefficient.

7. Conclusions

The obtained results allow to conclude that the developed technology of monitoring horizontal displacements of elongated hydraulic structures, in addition to testing their stability, enables also assessment of accuracy of this method. Values of horizontal displacement, determined as a result of control measurement, indicate stable behaviour of the assessed hydraulic structure, which is a set of pressure pipelines with supports embedded in the slope of the hill. The assumed accuracy of the determination of horizontal displacement component parallel to the pipe axis (Y–axis of the coordinate system) was achieved. Constructing a special adapter for centering the EDM prism and the target plate over a benchmark enabled quick and precise measurement of distances and angles. A special extended measurement and control network, as well as assumptions and methodology of least squares adjustment contributed to determining the Y component precisely, despite the limitations of configuration and land cover. The adopted methodology for taking measurements and analysis of results made it possible to achieve satisfactory results in terms of accuracy without the need to establish new survey marks. To ensure the proper safety control of support and pressure pipeline groups, further surveying monitoring of this object is planned in the coming years.

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System wyznaczania poziomych przemieszczeń podpór rurociągów ciśnieniowych wzdłuż stoku zbocza

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Streszczenie. Zespół Instytutu Geodezji i Kartografii od kilkunastu lat prowadzi geodezyjny monitoring stanu bezpieczeństwa jednej z polskich budowli hydrotechnicznych, a mianowicie Elektrowni Wodnej Żarnowiec. W obliczu katastrof budowlanych spowodowanych osuwiskami ziemnymi, które miały miejsce na świecie w ostatnich latach, rozszerzono zakres monitoringu obiektu o badania stabilności żelbetowych podpór rurociągów ciśnieniowych znajdujących się na stoku zbocza. Niniejsza praca dotyczy opisu metody jaką opracowano dla tego celu. Obejmuje ona zaprojektowanie i wykonanie nowatorskiego przyrządu, który pozwala wykorzystać istniejące znaki sieci pionowej jako punkty do badania przemieszczeń poziomych. Opisano konstrukcję tego przyrządu, która umożliwia ustawianie pryzmatu dalmierczego nad różnymi rodzajami reperów. Omówiono także aspekty doboru nietypowego kształtu specjalnej osnowy geodezyjnej. Przedstawiono również sposób opracowania wyników pomiarowych oraz dokonano analizy uzyskanych wyników przemieszczeń punktów kontrolowanych.

Słowa kluczowe: monitoring, osuwiska, przemieszczenia, podpory rurociągów