Anna Szafarczyk*, Anita Kwartnik-Pruc*

The Concept of an Integrated Monitoring System for Surface Mass Dislocations Using Terrestrial Radar Interferometry**

1. Introduction

According to the *Act of 18 April 2002 on the state of natural disasters*, landslides are classified as natural disasters and if their consequences threaten the life or health of large numbers of people, grand-sized property, or the environment in major areas – then these landslides are classified as natural disasters.

The first record of natural landslides, conducted in the late 60's of the twentieth century, revealed the existence of more than 3,000 landslides on the Carpathian slopes, whose numbers increased to 20,000 in the course of further exploratory works. Over the past several years, after heavy rainfalls or spring thaws, landslide movements have been renewing consistently, destroying residential and farm buildings, frequently posing a threat to human life and health at the same time.

Threats of landslide dislocations in mining areas are equally serious and dangerous. Open-cast mining, carried out without continuous monitoring of slope deformation processes, could result in a threat to the life of a mining crew, and it would incur the financial losses to the mining company, associated with the destruction of the equipment and discontinued mining operation. The case in point are the great landslides in the open-cast lignite mine "Bełchatów", which expose the mine to various risks and incur losses of deposits up to tens of millions of zloties [4].

* Faculty of Mining Surveying and Environmental Engineering, AGH University of Science and Technology, Krakow

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2. Surveys of Landslide Processes

Landslide processes are characterized by a prolonged course and they usually involve several stages of development, which occur sequentially with various severity and frequency, depending upon the changing geological and geomorphological conditions, as well as upon the intensity of the factors affecting the activation of rock masses.

Knowledge of the course of successive stages in the landslide process allows a more accurate assessment of the direction of further development of a specific form, and it is necessary for an appropriate determination of geological and engineering estimates of the slope stability. Due to the pertinence of the landslides problem, various studies on their identification, registration and monitoring have been carried out over the past several years. Costly geological and geotechnical research was conducted, selected areas were protected against the effects of the landslide slopes which were getting activated, and the use of modern surveying technologies in the battle against landslides was analysed. Upon the decision of the Environment Minister, a program of Anti-landslide Protection System SOPO was introduced, which is a project of nationwide significance, and whose primary objective is to identify, document and mark on the map in a scale of 1:10 000 all landslides and areas potentially at risk of mass movements in Poland, as well as to install a deep-seated and surface monitoring system of 100 selected landslides. The whole project is to support local authorities in carrying out duties relating to the problems of mass movements, which arise from the relevant laws and regulations.

3. Geodetic Monitoring of Landslides

Geodetic monitoring of surface mass movements includes carrying out topographic surveys of a network of points fixed on the studied slope. The points are usually fixed in a form of pins. At the upper end of the pin, a head equipped with a centring mark is studded, and it also allows to conduct levelling survey. For soft to intermediate hardness of the soil, the used pins are made of aluminium or steel, and for solid objects or rocks brass bench-marks are used, with the possibility of screwing a distancemeter prism.

Geodetic technologies of monitoring landslide risk areas are based on measuring the spatial XYH network performed in a classical manner or supplemented by GPS surveying, and alternatively on the levelling network surveying. Additionally, the surveys may be carried out in control lines or in the rosettes of points

constituting the expansion of the control lines [5]. The slope surface may also be subjected to laser scanning with the use of a terrestrial laser scanner or scanning total station, and it also may be inventoried using photogrammetric methods.

4. Monitoring of Landslides Using Terrestrial Radar Interferometry

The authors, who take up the subject of improving safety in landslide areas, suggest the enhancement of the currently used techniques of monitoring landslides with an innovative, still not used in Poland, terrestrial radar interferometry method. This method uses an interferometric radar called IBIS L (Fig. 1).

Fig. 1. IBIS L instrument

This is a precise microwave surveying test equipment used for remote non-contact surveying of dislocations and deformations of engineering structures as well as of the land surface, with the accuracy and frequency which has been unattainable in the hitherto existing practice [1]. The base of the device is a radar working in the KU-band (17.1–17.3 GHz, wave from the band of 17.2–17.4 mm), allowed on the territory of the EU, which uses synthetic aperture method (In-SAR.), previously used exclusively for satellite surveying. The radar emits of a coherent scanning beam of electromagnetic radiation of very small power and stepwise variable frequency and direction towards a test object, and then receives, records and analyses the reflected signal. The built-in interferometric system conducts precision surveying of the phase change of the reflected signal against the transmitted signal, allowing the surveying of dislocations of selected points or areas of the test object (pixels) with a resolution of 0.01 mm and the frequency of

200 Hz, while the test object may be located at the distance of 0.01–4.0 km from the instrument and the distinguishability of pixels is achieved with changing the distance by 0.5–0.75 m and the azimuth by 4.5 mrad.

One of the main manners of the radar interferometer applications is detection, monitoring and prediction of slope instability (especially of high slopes, open-cast mines), of dams of post-floatation waste reservoirs as well as land and building deformations in the mining areas. Resolution of the IBIS-L interferometric radar allows to detect and analyse the radial motion of a dam of post-floatation waste reservoir, or an open pit slope with an unprecedented resolution of 0.1 mm, inaccessible to total station monitoring, photogrammetric monitoring, or monitoring using GPS system.

Such high accuracy allows the earliest possible detection of landslides, mass movements, from solifluction to catastrophic events at their initial stage, and then monitoring the course of events with virtually any resolution in time.

Having at disposal such a unique measuring device makes it possible to detect dislocations at their initial stage, therefore allowing to warn of an approaching danger of soil stability loss and hence to raise the level of security.

No research has been conducted in Poland so far including the use of terrestrial radar interferometry for monitoring landslides. This subject was dealt with by an Italian team of scientists led by prof. M. Pieraccini [5, 6]. Successfully carried out surveys were continued by a team of prof. G. Bernardini and they were presented in the subject literature against the example of monitoring Tessina landslide in Italy (Fig. 2).

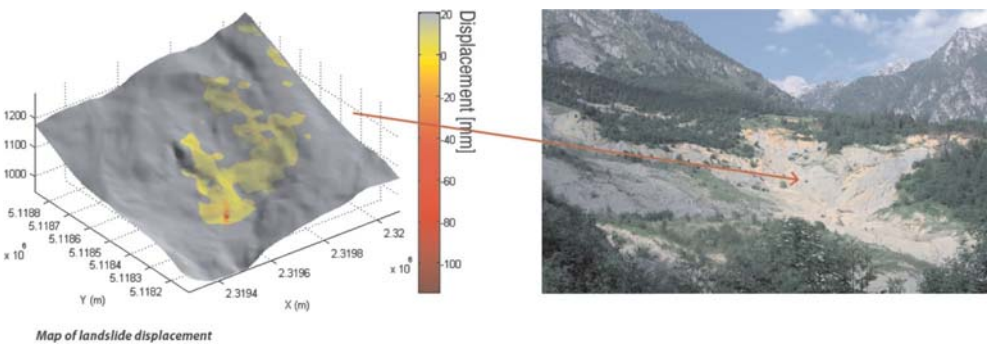

Fig. 2. Map of the area dislocations determined with IBIS-L interferometric radar

According to the manufacturer, one of the main directions of the IBIS-L radar interferometer applications is detection, monitoring and prediction of instability of various types of slopes, dams of post-floatation waste reservoirs, as well as land and building deformations in the mining areas. As it is certified by the available

literature and preliminary tests, which have already been conducted by our team, the use of terrestrial interferometric radar for measuring stability of natural slopes and those artificially created by man, provides results, which are qualitatively and quantitatively superior to those obtained from the existing methods of observation applied hitherto (higher than previously achieved accuracy of dislocation surveying, possibility of virtually continuous monitoring, becoming independent from geodetic control network).

5. The Concept of an Integrated Landslide Monitoring System

Due to the limitation of radar interferometry method to determine the value of dislocations, the surveys should be complemented with the use of classical geodetic techniques (GPS and tacheometry), which additionally will help to set the dislocation directions and determine the values of horizontal strains of the area.

Implementation of integrated surveying will allow the designation of:

- horizontal dislocations of a selected part of the slope (using the IBIS L interferometric radar),
- vertical and horizontal dislocations together with their direction of occurrence (using GNSS surveying),
- horizontal strains of selected sides (with the use of tacheometric TPS surveying),
- layers of land slips (using ground penetrating radar),
- defining the profile and manner of layer deposition (using penetration probes),
- determination of moisture content, granulation, bulk density, consistency limits and plasticity level (laboratory tests of physical properties of the samples).

The conducted geological and engineering studies will help to determine the impact of geologic structure and soil properties on the possibility of landslide occurrence. The starting point of the planned surveys on the morphology of a selected landslide should be in the first place the analysis of the study results previously conducted by various authors, which will allow to capture the main directions of the changes taking place across the various forms of landslides. Genetic conditioning, range and nature of the development of landslide forms are closely dependent upon the regional geology and relief, and that is the reason why the initial objective should be to determine the characteristics of the relief of selected landslide areas as well as their geological situation [2, 3].

The scope of geological survey should comprise the identification of geological and engineering conditions of the observation area, including the structure of the slopes, the nature and physical-mechanical properties of the soil, as well as conducting a numerical analysis of the slope stability. For this purpose, several shallow penetrometric holes should be made in order to assess the nature of landslide colluvia, and tens of soil samples should be taken for laboratory testing.

Satellite surveying of landslide dislocations can be carried out with one of the following surveying procedures: static, rapid static or kinematic in real time in relation to the physical and virtual reference station (VRS) implemented in Poland within the ASG-EUPOS network system. Selection of a surveying procedure may depend upon several factors identified in the course of field research, and which include the following: area topography, interference of GPS signals, planned precision, the number of points and the distance between them.

The surveying of the soil slip layers in the area of the surveyed landslides should be conducted with GPR. This surveying, monitored with the GNSS system, or TCA total stations provide a possibility of potential three-dimensional modelling of identified lithological boundaries and consequently the possibility of identifying the topographic and depth range of a landslide. Observation periods must be adapted to the pace of the occurrence of deformations.

The effect of the proposed surveys will be obtaining discrete values of the deformation indices related to the points of the surveying control network which are fixed on the slope of a landslide, and maps of dislocations for anthropogenic and natural slopes subject to the survey. In addition to the maps in the classic, current form which is based on the presentation of selected points vectors of dislocations, maps viewing the entire area in the form of pixels of a certain colour will appear, a shade of which, according to legend, will correspond to the specific value of the dislocation. Applying a broad spectrum of geodetic surveying methods allow the determination of internal and external monitoring accuracy using terrestrial radar interferometry.

The obtained results enable to establish a comprehensive surveying system allowing precise monitoring of surface mass movements.

6. Summary

Integration of surveys carried out with the use of an interferometric radar with the hitherto existing surveying techniques in geodesy will be a new, unprecedented in Poland, method of monitoring, and the diagnosis (even preliminary) of kinematics of movements will allow timely implementation of precise surveying.

The application of several mutually complementary geodetic surveying techniques complemented with the abundant research material regarding geological and engineering database of the subsoil building a particular landslide, will allow the determination of landslide process kinematics with an unprecedented accuracy. Obtaining positive test results will give rise to implementation of this new system also in other fields which may be the monitoring of the embankment slopes located in the vicinity of roads and motorways, or modelling of thermal deformations of large water dams.

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