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# GEOPHYSICAL INVESTIGATIONS OF THE CARPATHIAN SLIDE SLOPES

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**Abstract**. Application of geophysical methods as part of the old landslide stability determination and forecasting stability for Carpathian slopes is described. Physical base of the seismic refraction and electrical-resistance methods have been outlined in view of the tasks which are to be solved, namely delineation of the landslide geometry, especially depth and shape of the slide boundary, and horizontal range of the slide. Geophysical classification index KFG with adjustment factors proposed by Romano used for preliminary evaluating and forecasting the stability of flysch rock slopes, have been presented. Some examples of seismic refraction and electrical-resistance methods for geometrical definition of landslide on the area of Carpathian flysch have been outlined. All experiences of geophysical investigations of the Carpathian landslide slopes were gathered on the basis of investigations for over hundred landslides, on water reservoir slopes, mainly.

**Key words**: landslide slope, slide boundary, seismic refraction method, electrical-resistance method, classification index KFG, Slope Mass Rating (SMR).

**Abstrakt**. W artykule omówiono zastosowanie metod geofizycznych w badaniu i prognozowaniu stateczności karpackich stoków. Przedstawiono podstawy fizyczne wykorzystania metody sejsmicznej refrakcyjnej i geoelektrycznej elektrooporowej dla rozpoznania geometrii istniejących osuwisk, w szczególności głębokości i przebiegu strefy poślizgu oraz poziomego zasięgu zsuwu. Wskazano na możliwość wykorzystania indeksu KFG geofizycznej klasyfikacji fliszu, po wprowadzeniu wskaźników korygujących zaproponowanych przez Romano, do wstępnej oceny i prognozy stateczności karpackich stoków.
Przedstawiono przykłady zastosowania metody sejsmicznej refrakcyjnej i geoelektrycznej elektrooporowej do określenia przebiegu strefy poślizgu i poziomego zasięgu zsuwu osuwisk wykształconych na fliszowych zboczach Karpat.
Doświadczenie zdobyte na podstawie badań ponad stu osuwisk, zlokalizowanych głównie na zboczach sztucznych zbiorników wodnych, wykorzystano w badaniu karpackich stoków osuwiskowych metodami geofizycznymi.

**Słowa kluczowe**: zbocze osuwiska, strefa poślizgu, metoda sejsmiki refrakcyjnej, metoda elektrooporowa, indeks KFG, współczynnik SMR.

## INTRODUCTION

Carpathian slide slopes built up from alternate "hard" sandstones and "soft" shales are vulnerable for loss of stability if equilibrium of forces at the slope will change. This will occur after long and/or intensive rainfall. In 2000 and 2001, several old and some new landslides were activated after long rainfall periods.

Study of the Carpathian slides started in 1970 as a part of State Program PR-7 *Technical conditions for hydraulic constructions and shoreline of water reservoirs*. Over 100 landslides have been investigated at the slopes of Tresna, Myczkowce, Solina, Dobczyce, Świnna–Poręba, Czorsztyn–Niedzica and Krempna reservoirs. As a result of these investigations, methodology of the field geophysical investigations for the slope landslides have been elaborated. These investigations were based on the seismic refraction and electrical-resistance methods. Results of these investigations have been presented at the international and national symposia (Bestyński, Trojan, 1975; Bestyński, 2001; Farbisz, Honczaruk, 2002). Recently, several new techniques have been implemented, such as seismic share waves $V_{SH}$ registration, resistance of the underlying rocks representation by using tomography processing and GPR (ground penetration radar) techniques. In the paper, conditions for implementing geophysical methods at the landslide slope investigations and some of the field cases are presented.

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## GEOPHYSICAL METHODS IN THE LANDSLIDE SLOPES INVESTIGATIONS

Some well-known methods are used for the slope stability calculation, and to use these methods, landslide geometry and mechanical properties of the rocks especially from the vicinity of the slide boundary must be known (Bestyński, 1992; Thiel ed., 1995; Bober *et al.*, 1997). Some geophysical methods are used for delineating landslide geometry.

The main purpose for using geophysical methods is as follows. Landslide changes the rock (soil) structure by increasing porosity and decreasing geo-technical properties. Additionally, in the vicinity of the slide boundary there is often a water level. The aforementioned reasons will increase vulnerability of the slopes for sliding because of weak geo-technical properties and higher specific gravity of the rocks. All these conditions will change propagation of the seismic waves and electrical resistance of the rocks.

In case of seismic method, longitudinal waves $V_P$ and shear waves $V_{SH}$ are commonly used. Velocity of the seismic wave decreases with the increasing porosity and the decreasing geotechnical properties of the rocks. Electrical resistance decreases with water presence in the rocks. On the base of the seismic wave velocity and electrical resistance, it is possible to evaluate geotechnical class of the flysch rocks. Geotechnical class KFG is equivalent to the RMR Bieniawski's class. Using RMR class and Romano's method the SMR (Slope Mass Rating) class could be evaluated (Romano, 1985). This SMR class describes vulnerability for loss of the slope stability.

SMR classification number is based on the classification index KFG or RMR with additional coefficients $F_1$, $F_2$ and $F_3$ responsible for the system of layers and slope inclination and cracks. Additionally, correction coefficient $F_4$ responsible for the slope undercutting (if/any) is implemented.

$$\mathrm{SMR} = \mathrm{KFG} - (F_1 \cdot F_2 \cdot F_3) + F_4$$

where:

$$\mathrm{KFG} = 11.78 - 2.8 \cdot 10^{-3}\rho + 3.8 \cdot 10^{-3} V_P + 3.34 \cdot 10^{-5}\, \rho V_P$$

$F_1$, $F_2$, $F_3$ and $F_4$ — correction coefficients.

Usage of the SMR class gives possibility to estimate vulnerability of the slope stability loss at the project planning stage, and this is the main advantage of this method.

Seismic method (refraction profiling) and electrical-resistance method (profiling and vertical sounding) are standard geophysical methods used for lithology, tectonic, geometry and thickness of the weathered zone investigations on the Carpathian landslide slopes. In some field cases, thermal, acoustic, electrical tomography and GPR methods have been used. Tomographical resistance mapping of the underlying rock is much more accurate than traditional methods, therefore it is used for delineating horizontal range of the slide and the slide boundary. The GPR method based on the recorded reflection of the electromagnetic wave propagation is useful in shallow landslide investigations.

Seismic investigations have been used also during the stabilisation of the active landslides. As a result of the slope undercutting near the inlet power tunnels at the Świnna–Poręba dam site, structural landslide above the towers have been activated. This landslide had to be stabilised by the roof bolting and gunite method. To use this method, the thickness of the loose rocks must have been determined, and this was done by the seismic refraction method. After landslide stabilisation, seismic investigation confirmed the increase of the geotechnical properties of the rocks through recording the increase of the seismic waves velocity.

## FIELD CASES

**Czorsztyn–Niedzica Landslide**. The landslide is an old stable formation located at the left shore of the reservoir, about 1500 m from the dam (Fig. 1). Because of the possibility that after reservoir's infilling landslide could be activated, stability of the landslide has been calculated. Position of the slide boundary has been delineated by seismic refraction profiling (longitudinal waves $V_P$ and shear waves $V_{SH}$) and checked by pits from which samples of the rocks have been collected for laboratory measurements of geotechnical parameters. Position of the slide boundary, delineated by using $V_P$ and $V_{SH}$ seismic waves, coincides with the boundary visible in the pits (Fig. 2A, B).

**Międzybrodzie Żywieckie Landslide**. Landslide in Międzybrodzie (Fig. 3A, B) is developed in sandstone flysch rocks due to undercutting of the slope during the construction of the pumped-storage water power station Porąbka–Żar. Horizontal range of the slide was delineated by electrical resistance method, and depth of the slide boundary by seismic refraction method.

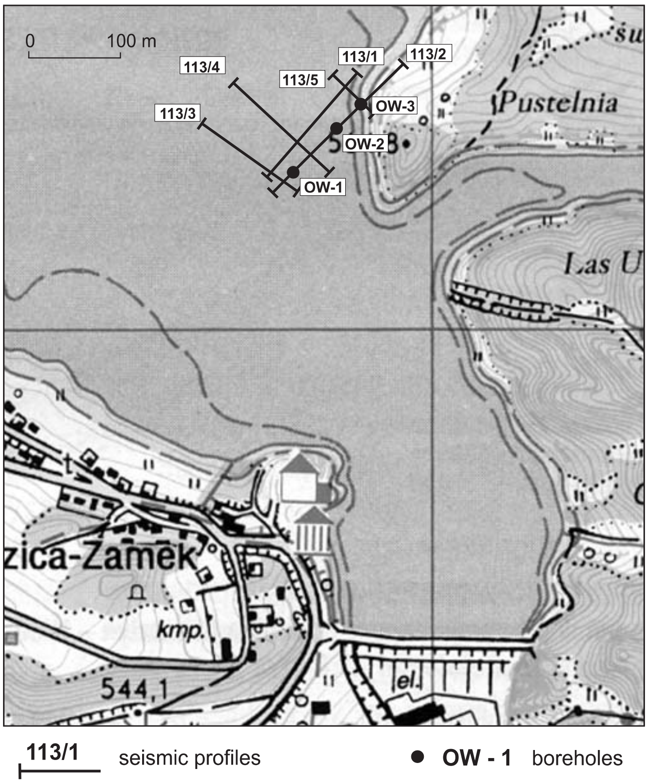
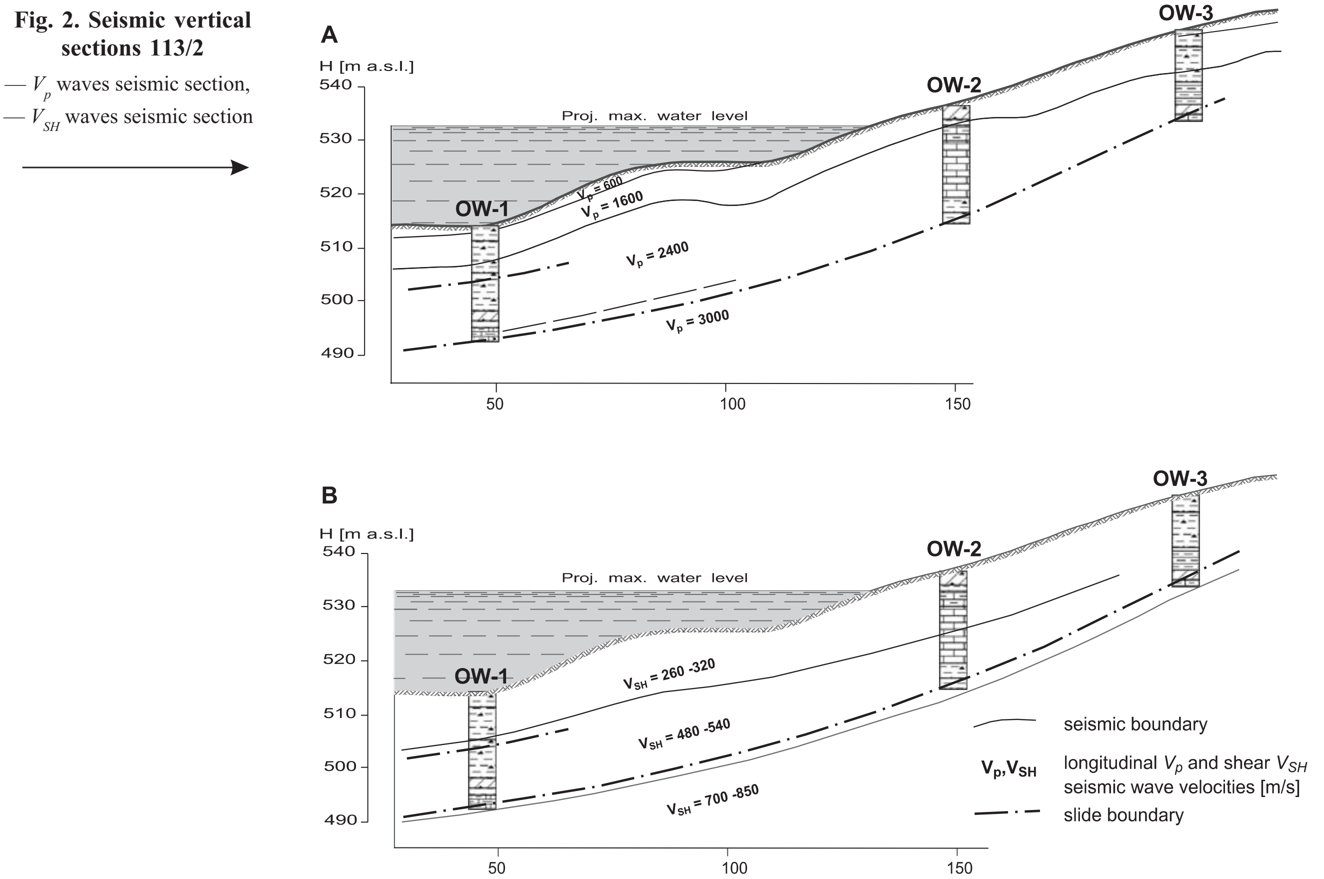



**Fig. 1. Location of seismic profiles and boreholes at the landslide number 113; Czorsztyn–Niedzica water reservoir**

**Fig. 2. Seismic vertical sections 113/2**

**A** — $V_p$ waves seismic section,

**B** — $V_{SH}$ waves seismic section



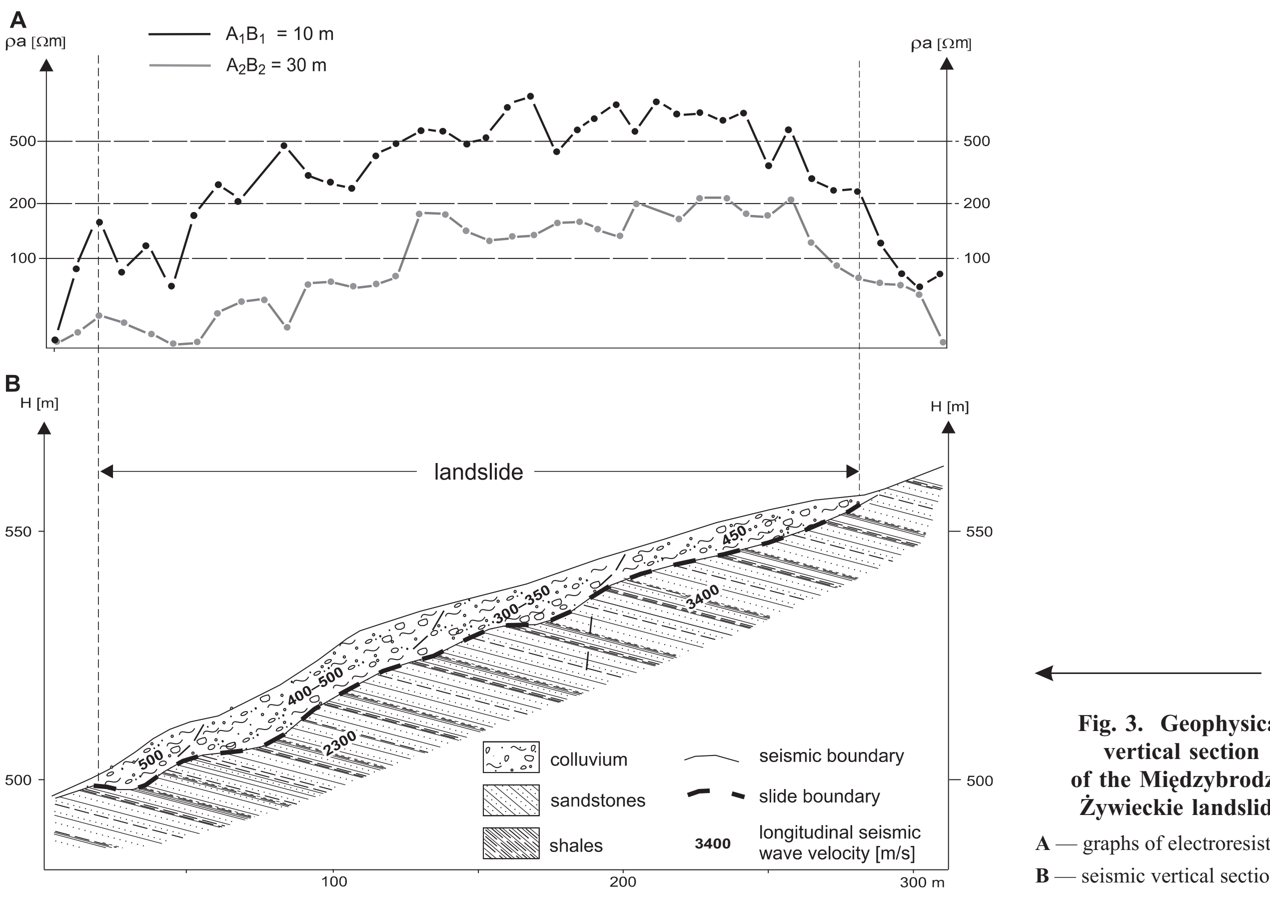




**Fig. 3. Geophysical vertical section of the Międzybrodzie Żywieckie landslide**

**A** — graphs of electroresistivity,

**B** — seismic vertical section

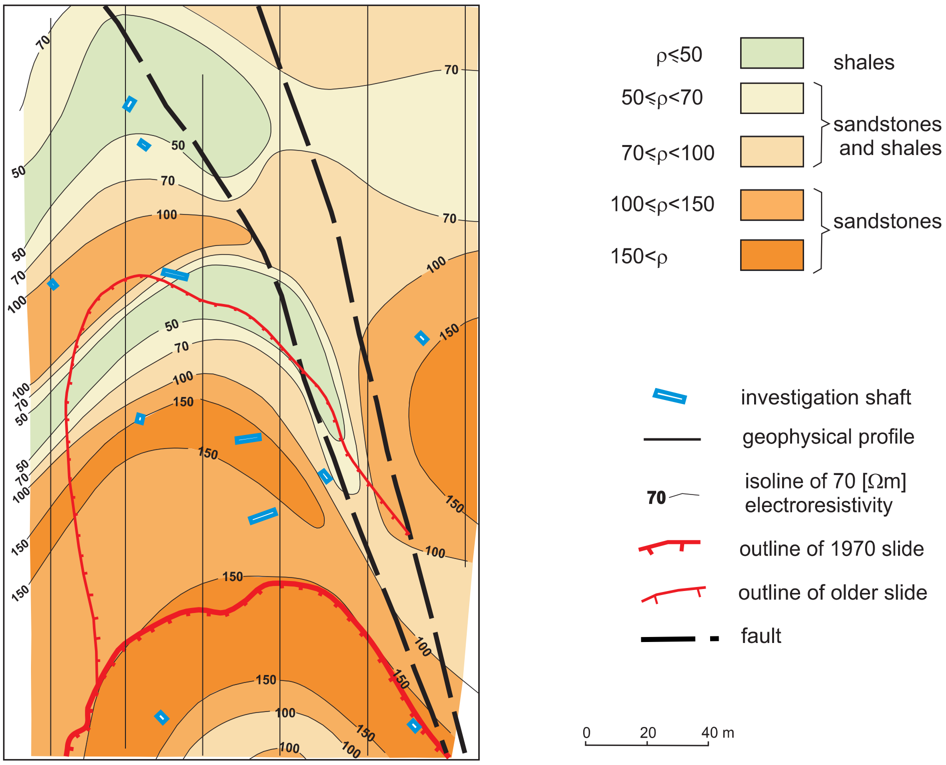



**Fig. 4. Map of electroresistivity of Lipowica mountain slope**

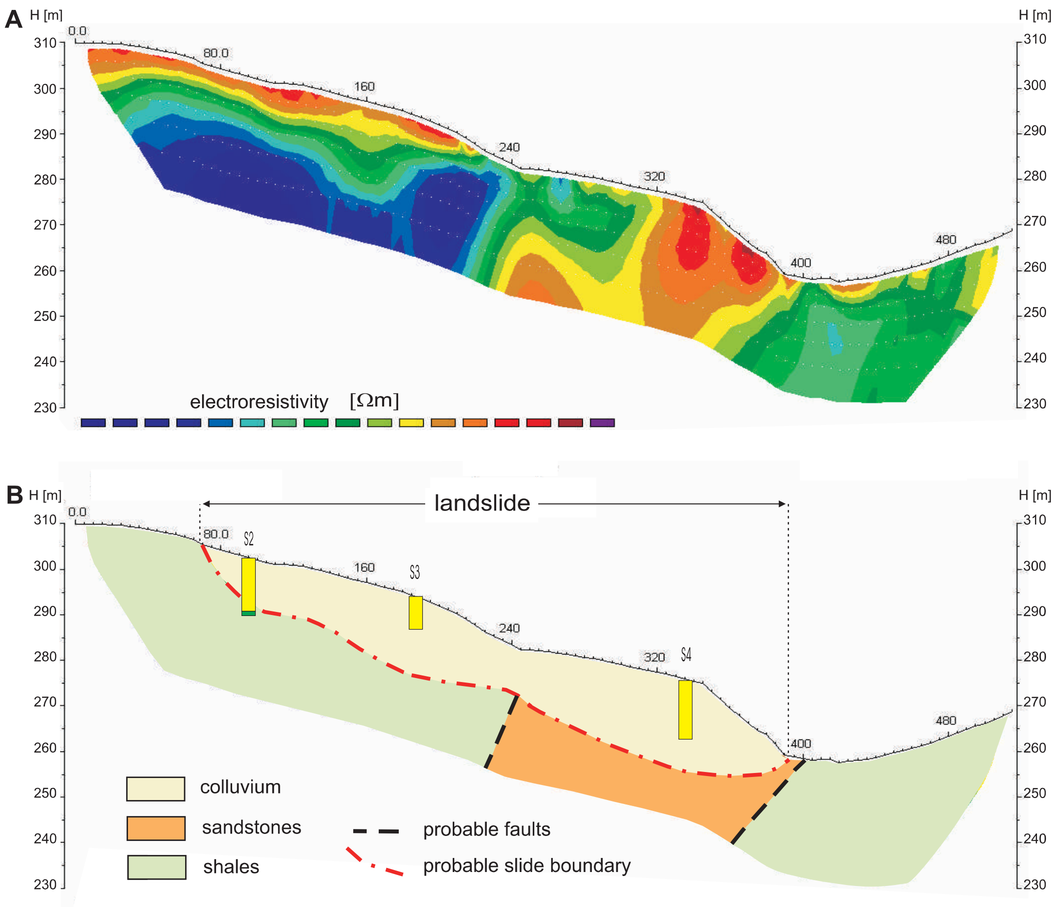



**Fig. 5. Geophysical results of Dubiecko landside investigations**

**A** — distribution of electroresistivity obtained by tomographical processing; **B** — geological interpretation of the results from the Figure 5A

**Lipowica Landslide**. Landslide is located near Lipowica quarry, on the slope with several old landslide formations. Lithology consists of thick-layered sandstones. Electrical resistance method has been used and deta ils of lithology of the top layer and tectonic faults were delineated (Fig. 4). Geological map on the basis of geophysical results has been worked out and checked by geological pits.

**Dubiecko Landslide**. Landslide is an old stabilised slide on the slope of the San River. Along the main axis of the landslide, electrical resistance investigations have been done and results have been processed by using tomography method. This method required measurements of horizontal and vertical continuous distribution of electrical resistance. It was achieved by the field lay-out of the electrodes and special measurements procedure. Because of the difference in the loose and solid rocks resistance, it was possible to delineate slide boundary of the landslide. Some examples of the measurements done by PBG-Warszawa are displayed on the Figures 5A, B.

## CONCLUSIONS

**1**. Seismic refraction and electrical-resistance methods are used for investigations of the Carpathian slopes for over 30 years. These methods are used for delineating landslide geometry and position of the slide boundary.

**2**. By using KFG geotechnical class of the rocks, Romano's method for preliminary estimation of slope's stability could be implemented.

**3**. Seismic refraction and electrical-resistance methods are the most effective, while in favourable conditions GPR (ground penetration radar) method could be used.

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