WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.141874
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVIII ISSUE 3 2022

pp. 71 – 85

Research paper

Geophysical investigation and the use of their results in the evaluation of the stability of slopes of artificial water reservoirs in the flysch Carpathians

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Abstract: The article presents the possibility of using geophysical surveys to assess the stability of Carpathian slopes built of flysch deposits susceptible to mass movements. Landslide slopes located in the coastal zone of artificial water reservoirs are particularly susceptible to the loss of stability due to the erosion of this zone and the changing water level in the reservoir. Geophysical surveys of landslides carried out as a part of the research programs: PR-7 carried out by IMGW in 1972–1980 and SOPO carried out by PGI in 2009–2016 made it possible to develop a methodology of geophysical surveys enabling the determination of the geometry (course of the slip surface and range levels) of the existing landslides, information necessary to carry out a computational analysis of their stability. Examples of geometry of landslides in the coastal zone of the Czorsztyn reservoir and landslides in the area of hydrotechnical drifts of the Świnna-Poręba dam were presented. The possibility of a quantitative evaluation of the stability of the Carpathian slopes was also proposed on the basis of the *SMR* (*Slope Mass Rating*) proposed by M. Romana, using the *KFG* (*Klasyfikacja Fliszu-Geofizyczna*) geophysical classification equivalent to the *RMR (Rock Mass Rating)* classification by Z.T. Bieniawski for the assessment of the massif. A dozen or so active landslides were compiled for which the stability was determined using the *SMR* method.

Keywords: geophysics, hydroengineering, landslides

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1. Introduction

The accumulation of water in the artificial dam reservoir changes the stability conditions of the slopes in the bank zone of the reservoir. The factor causing this change is the abrasion of the banks and the change in hydrogeological conditions. Landslide slopes threatening the existing and planned elements of technical infrastructure must be subject to detailed geological and geotechnical surveys aimed at assessing their stability and designing possible stabilizing measures. The areas where the Czorsztyn–Niedzica, Dobczyce, Besko, Klimkówka and Świnna Poręba dam reservoirs have been built in recent years as well as the planned dam reservoirs, are built of flysch formations susceptible to stability loss.

The alternating layers of hard and cracked, therefore susceptible to rainwater load, sandstone and shale, the strength of which decreases under the influence of hydration, create a structure very susceptible to mass movements, which builds flysch. Especially when the fall of the layers is close to the slope inclination [6]. Geological surveys and observations made in the Carpathians, after extremely intense rainfall in 1997, 2001 and 2010, documented 58,000 landslides. In the vast majority of cases, these were old, previously stable landslides, especially susceptible to the activation of mass movements.

The quantitative method of assessing the slope stability is a computational analysis based on the comparison of the sum of the sliding forces and the supporting forces of the rock material susceptible to slide (colluvium) [13]. To make it, it is necessary to know the geometry of the slope (the course of the slip surface and the range of colluvial) and the mechanical parameters of the material from the slide surface. One of the research methods used to identify the geological structure and physical parameters of rock media, including landslide slopes, are geophysical methods.

The use of geophysical methods in the identification of flysch landslide slopes was initiated already in the 1970s by the Carpathian Department of the PGI. The results of the seismic and electroresistivity tests carried out at that time on nine Carpathian landslide slopes were summarized in a paper presented at the 13th Conference of the Rock Mechanics Subcommittee of the Polish National Committee of the International Commission on Large Dams [1]. Further studies of the landslide slopes were carried out in the coastal zones of the Tresna, Myczkowce, Solina, Dobczyce, Czorsztyn–Niedzica and Świnna Poręba reservoirs. These studies confirmed that the seismic refraction and electroresistivity methods are the optimal set of geophysical methods in the study of flysch slopes [12].

These methods enable the mapping of the geometry of the landslide necessary for computational analysis. To perform the computational analysis, it is also necessary to know the parameters of the material from the slip zone. Obtaining them requires drilling on hard-to-reach landslide slopes. Therefore, a method is sought that would enable a quick quantitative assessment of slope stability, without the need to perform or significantly reduce costly and time-consuming drilling.

Such a method was proposed by M. Romana [8, 9] presenting the *SMR* (*Slope Mass Rating*) classification, which determines the slope stability based on the geotechnical class *RMR* (*Rock Mass Rating*) [5] of the massif building the slope and the mutual relations of the dip angles and the extent of the slide surface and the slope surface. In the case of flysch massifs, the geotechnical class of the massif can be determined on the basis of the *KFG* (*Klasyfikacja Fliszu-Geofizyczna*) classification based on geophysical parameters and the equivalent *RMR* classification [2, 4]. Thus, geophysical surveys allow not only to determine the geometry of the landslide, but also to quantify its stability based on the *SMR* classification.

2. Principles of selection of geophysical methods

The slide of the rock material, causing its cracks and loosening, also results in a decrease in the strength of the material and a decrease in the velocity of longitudinal seismic waves Vp. On the border of the colluvium and the intact rock massif, which is the surface of the landslide slide there is a rapid increase in the velocity of seismic waves. At such a border, a refractive wave is formed. Thus, the measurements of the seismic refraction profiling method enable the mapping of the course of the landslide slide surface.

The slide of rock masses also causes an increase in their porosity and the associated dehydration of the medium, resulting in an increase in its electrical resistance ρ. Based on the differentiation of the electrical resistance, it is possible to determine the range of the slide. The mentioned geophysical parameters Vp and ρ not only allow to determine the geometry of the landslide, but also to determine the lithology and tectonics of the slope, which determine its geotechnical class and susceptibility to mass movements. The electrical resistance of flysch composed of alternating layers of hard and high-resistance sandstone as well as soft and low-resistance shale depends on its percentage composition. The lithological composition of flysch can therefore be determined with a satisfactory accuracy, on the basis of the empirical dependence determined for flysch in the form of:

$$[\%\ \text{sandstone}] = f(\rho) \tag{2.1}$$

In turn, the velocity of seismic waves in a rock medium is related to its modulus of elasticity and porosity with theoretical and empirical relationships in the form of:

$$Ed = f(Vp,\ Vs), \qquad Kp = f(Vp) \tag{2.2}$$

The two mentioned geophysical parameters also define, synthetically, two groups of parameters describing the class of geotechnical rock massifs. The first of them include the parameters determining the strength of the rock material and the degree of its fragmentation and are described by the velocity of longitudinal seismic waves Vp, and the second are the parameters determining the friction between the rock blocks building the massif, depending on the type of surface and waterlogging, described by the electrical resistance ρ. On the basis of these two parameters it was possible to determine the geotechnical class of flysch massifs *KFG*, equivalent to the *RMR* class and use it to quantify the stability of flysch slopes based on the *SMR* classification.

The *KFG* classification was developed on the basis of geophysical studies and geotechnical observations of flysch massifs at 20 measurement sites located throughout the

Carpathian Mountains and representing lithologically and tectonically diverse flysch massifs. The measurement stations where the values of Vp, ρ and RMR were determined were located in the research tunnels. The KFG value, equivalent to the RMR value, was determined by the approximation method in the space Vp, ρ, RMR.

The geotechnical class of KFG is determined by the formula:

$$KFG = 11.8 - 0.0028\rho + 0.0038Vp + 0.000033Vp \cdot \rho \tag{2.3}$$

where:

Vp [m/s] – velocity of longitudinal seismic waves,

ρ [Ωm] – electrical resistance.

The SMR classification, as already mentioned, makes the stability of the slope dependent on the strength of the rock material that builds it, described with the geotechnical class RMR (KFG) and on the mutual relations between the directions of sliding forces and the direction of the slide, as well as the method of remodeling and erosion of the slope. This relation is taken into account by introducing correction factors: F_1, F_2, F_3 and F_4.

The SMR class is determined by the formula:

$$SMR = KFG + (F_1 \cdot F_2 \cdot F_3) + F_4 \tag{2.4}$$

where:

F_1 – coefficient depending on the relation of the slope extension and the slide surface extension,

F_2 – coefficient depending on the dipping angle of the slide surface,

F_3 – coefficient depending on the relationship between the slope dipping and the slide surface dipping

F_4 – coefficient dependent on erosion and mechanical remodeling of the slope.

The numerical values of the correction coefficients, determined empirically on the basis of observations of landslides of different geometry and geology [11], are as follows:

$F_1 = 0.64 - 0.006 \arctan[0.1(|\alpha j - \alpha s| - 17)]$,

$F_2 = 0.56 + 0.0051 \arctan(0.17\beta j - 5)$,

$F_3 = -30 + 0.33 \arctan(\beta j - -\beta s)$,

$F_4 = 0$ in the absence of erosion and remodeling of the slopes covered by the research, where:

αj – slide surface extension angle,

αs – slope extent angle,

βj – slide surface dip angle,

βs – slope dipping angle.

For a slide surface parallel to the slope surface: $\alpha j = \alpha s$ and $\beta j = \beta s$.

Depending on the value of the SMR classification number, 5 classes of stability of landslide slopes are distinguished; they are summarized in Table 1.

Table 1. *SMR* stability classes of landslide slopes

Blass number	V	IV	III	II	I
SMR value	0–20	21–40	41–60	61–80	81–100
rock mass description	very bad	bad	normal	good	very good
slope stability	completly unstable	unstable	partly stable	stable	completly stable
slide surface	big planar surfaces	planar or wedge surfaces	single planar or wedge surfaces	separate blocks	no slide surface
slide probability	0.9	0.6	0.4	0.2	0

3. Research examples

3.1. Landslides in the coastal zone of the Czorsztyn reservoir

As part of the study of landslides in the coastal zone of the planned Czorsztyn reservoir, the geometry of two landslides developed within the flysch, located in the immediate vicinity of the dam, was determined. The obtained results were used for the computational analysis of their stability. Landslide *A* on the left bank of the reservoir, near the Czorsztyn Castle, is an extensive, stabilized, structural slide. with an area of approx. 3 ha and a colluvium thickness of up to 20 m. below ground level. The relatively small differentiation of the velocity of the *Vp* waves between the deeper layer of colluvia and the bedrock made it impossible to trace the course of longitudinal refractive waves *Vp* along the bedrock with the length of the measuring system used. The course of this border was traced using the transverse *Vsh* refractive waves. The location of landslide *A* in the photo of the dam area is shown in Figure 1, and the seismic geological cross-section along the axis of the landslide in part *A* of the figure. Seismic measurements of the *Vsh* waves made in the measurement grid allowed for accurate mapping of the course of both landslide slide surfaces.

This information, together with the mechanical parameters of the material from the slide zone, determined in the OW-1, 2 and 3 boreholes, constituted the basis for the calculation of the slope stability. The second of the aforementioned landslides, the *B* landslide, is located in the immediate vicinity of the Niedzica Castle, on the side of the inlets to the hydrotechnical drifts of the dam. Also in this landslide, tests were carried out in a grid of measurement profiles using longitudinal waves *Vp* and on one of the profiles also transverse waves *Vsh,* as a result, determining the thickness and range of colluvium and the course of the slide surface. The mechanical parameters of the material from the slide zone were determined on the basis of measurements in PO1G and PO2G boreholes. In the area of this landslide, two series of measurements were made after damming the reservoir, in 1997 and 2000. Measurements were made at different water levels in the reservoir. The aim of the research, as in the case of landslide A, was to determine the geometry of the landslide

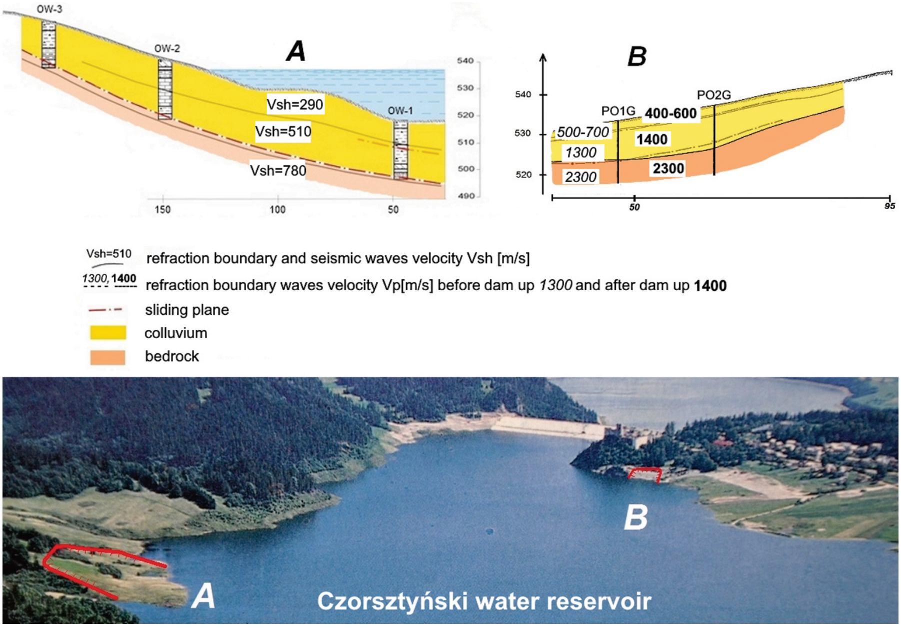

Fig. 1. Landslides *A* and *B* at the coastal zone of Czorsztyn reservoir; *A* – seismogeologic section along the axis of *A* landslide; *B* – seismogeologic section along the axis of *B* landslide

necessary for the computational analysis of its stability and to check whether the change in the water level in the reservoir affects the slope stability, also assessed here on the basis of the velocity of seismic waves in colluvium and rock subsoil. No such impact was found. The velocities of seismic waves, both in the colluvium and in the bedrock, did not change after the change of the water level in the reservoir. The location of the landslide is shown in Figure 1, and the seismic geological cross-section along its axis in part B of this figure.

3.2. Landslides in the area of the hydrotechnical drifts of the Świnna Poręba dam

Another example of slope stability testing is the area of the hydrotechnical tunnels on the right abutment of the Świnna Poręba dam. There was a risk that earthworks related to the construction of inlet and outlet portals and inlet towers to hydrotechnical tunnels would violate the stability of the slopes. Seismic tests of the C slope in the area of the tunnel outlet portal showed high velocities of seismic waves in the rock bed (Vp = 3000 m/s), which, with the fall of the layers transverse to the slope of the terrain, creates favorable conditions for the slope stability. Removal of the loose overburden and shotcreting of the surface were considered sufficient to secure its stability. In the area of the D slope at the inlet to the tunnel, the situation is different. The velocity of seismic waves in the rock bed is low (Vp = 2000–2400 m/s – tectonic zone), and the fall of the layers is consistent and close in value to the slope of the slope. This creates very unfavorable conditions for its stability. Seismic tests to assess and monitoring the slope stability were performed in several series. The tests (series I) carried out in April 1989 determined the thickness of the overburden (potential colluvia) and the velocity of seismic waves in the overburden and the bedrock. During the excavation for the inlet towers, symptoms of landslide activity were found. The movement was stabilized by anchoring the overburden to the ground and shotcreting the slope surface. However, these works were carried out carelessly and after heavy rainfall at the beginning of 1990, the slide was reactivated. Another series of seismic measurements (series II) showed a clear drop in wave velocity in the overburden layers caused by the slide. In order to stabilize the slope, another series of deep anchoring was made to the solid roof of the rock massif, the depth of which was determined on the basis of seismic tests and shotcreting of the surface. Seismic tests performed after these operations (series III) showed an increase in the wave velocity in the layers of overburden (colluvia) to a level similar to that obtained after the first bolting and shotcreting. Another series of tests (series IV) was performed after the large-diameter hydrotechnical tunnels had been drilled. At that time, a slight decrease in the velocity of waves in the rocky bedrock was found, which was caused by the weakening of the massif during the drilling of the tunnels. The last series of tests (series V) was performed after the final lining was completed and the filling and consolidation cementing the massif was completed. The observed slight increase in the velocity of waves in the rocky bedrock was caused by the filling and consolidation cementation of the massif around the tunnels. In general, the velocities of seismic waves, both in the overburden layers as well as in the bedrock, determined by series III, IV and V measurements, did not change significantly, indicating stabilized slope stability conditions.

Table 2 summarizes the seismic wave velocities in the separated layers of the overburden and subsoil, obtained in successive measurement series on the slope in the vicinity of the tunnel inlets.

Table 2. Evolution of slope stability at the inlets of hydrotechnical tunnels

Date of research	Wave velocities Vp [m/s] in separate layers			Evolution of slope stability – stabilization works and geophysical research
	1	2	3	
IV 89	900	1500	2400	symptoms of instability – bolting and shotcreting – 1st series of tests
III 90	400	1150	2400	after heavy rainfall, activation of the slide – 2nd series of tests
X 91	800	1400	2300	deep anchoring and shotcreting – slope stabilization, – 3rd series of tests
X 93	800	1450	2100	after boring large-diameter tunnels – 4th series of tests
X 96	900	1450	2200	tunnel casing and filling and consolidation cementation – 5th series of tests

In the photo of the right abutment of the dam, Fig. 2, shows the location of landslide slopes at the inlets (D) and outlets (C) of the tunnels. In part C of the figure, a seismic geological crosssection along the axis of the landslide at the tunnels outlets is presented, and in part D of the figure, a seismic geological cross-section along the axis of the landslide at the tunnel inlets.

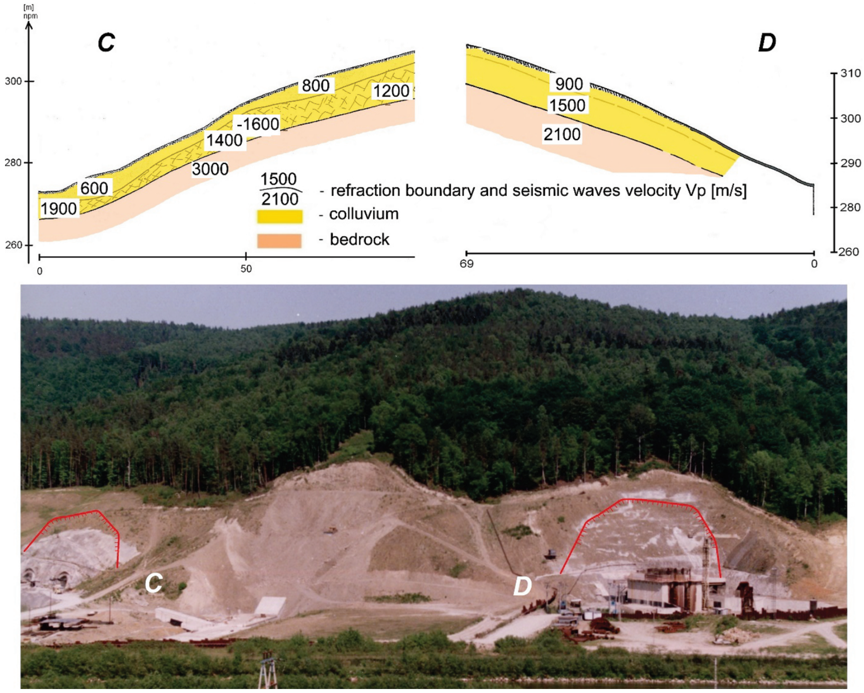

Fig. 2. Landslides *C* at the outlet and *D* at the inlet of Swinna Poreba dam hydrotechnical tunnels; *A* – seismogeologic section along the axis of *A* landslide; *B* – seismogeologic section along the axis of *B* landslide

4. The use of SMR classification in the stability assessment of flysch landslide slopes

Detailed studies of sixty Carpathian landslides carried out as part of the SOPO (Anti-Landslide Protection System) [7] program implemented by the PGI National Research Institute in 2009–2016, as part of which geological, geotechnical and geophysical surveys were performed, were an opportunity to check the accuracy of the stability forecast for flysch massifs based on the *SMR* classification. Unfortunately, only on 15 of the 60 mentioned landslides, geophysical, seismic and electroresistivity profiles ran in the immediate vicinity of inclinometric wells, which made it possible to compare the activity of the landslide found in the inclinometric wells with the forecast based on the *SMR* classification.

These landslides are summarized in Table 3 [3], giving the lithology and tectonics of the slope, the type of slide and the depth of the slide surface determined inclinometrically and seismically (refractive limit) as well as the values of the *KFG* and *SMR* classification numbers and the correction factors F1, F2 and F3. For all the listed landslides, the coefficient F4 = 0, because they were not subject to erosion and were not remodeled.

Table 3. Active Carpathian landslides covered by geotechnical and geophysical surveys

No.	Landslide	Lithology and tectonics	Slide type and cause	Landslide slope			*KFG* class [points]	Refraction boundary [m]	Correction coefficients			SMR class [points]	Range of KFG changes [points]
				Dip [°]	Slide surface [m]	Slide size [mm]			F_1	F_2	F_3		
1	JAMNICA	shales, sandstones (25%), fold disorders	consequent water infiltration	20	10.0	80	25.3	10.0	1.16	0.27	–30	15.9	22.2 ÷ 29.3
2	LACHOWICE	shales, marls, sandstones (10%) the post-fall zone	consequent water infiltration	14	13.5	100	25.2	12.5	1.16	0.21	–30	17.9	25.0 ÷ 30.0
3	KASINKA MAŁA	shales, variegated shales, sandstones (10%) no tectonic conditions	consequent water infiltration	17	11.5	pipe rupture	20.6	12.0	1.16	0.23	–30	12.6	19.0 ÷ 34.0
4	ŁĄCKO	shales, variegated shales, sandstones (15%). fold disorders	insequent water infiltration	13	11.5	125	23.1	12.0	1.16	0.20	–30	16.1	19.0 ÷ 35.0
5	ŻEGOCINA	shales, siltstones, sandstones (35%), close to fault zone	insequent water infiltration	20	11.0	22	28.5	13.0	1.16	0.27	–30	19.1	22.7 ÷ 33.5
6	MAKÓW Podhalański	shales, sandstones (30%) no tectonic conditions	insequent water infiltration	12	16.5	19	23.6	14.0	1.16	0.20	–30	16.6	21.6 ÷ 34.2

Continued on next page

Table 3 [cont.]

No.	Landslide	Lithology and tectonics	Slide type and cause	Landslide slope			*KFG* class [points]	Refraction boundary [m]	Correction coefficients			SMR class [points]	Range of KFG changes [points]
				Dip [°]	Slide surface [m]	Slide size [mm]			F_1	F_2	F_3		
7	KONIAKÓW	shales, variegated shales, sandstones (30%) overlap, close to fault zone	subsequent water infiltration	6	11.0	72	24.4	10.5	1.16	0.17	–30	18.5	21.5 ÷ 27.0
8	SZYMBARK – HUCISKA	shales, variegated shales, sandstones (10%) fold disorders	subsequent water infiltration, erosive leakage	7	14.0	55	19.8	11.0	1.16	0.18	–30	13.5	19.7 ÷ 22.7
9	CHOROWICE	Variegated shales, margl, sandstones (10%) overlap, fold disorders	subsequent water infiltration, erosive leakage	6	13.5	76	20.5	9.5	1.16	0.17	–30	14.6	19.0 ÷ 23.0
10	GRYBÓW	shales, variegated shales, sandstones (15%) overlap, fold disorders	complex water infiltration	10	7.5	78	21.3	8.0	1.16	0.19	–30	14.7	18.8 ÷ 23.7
11	JASŁO	shales, thin-bed sandstones. (20%) no tectonic conditions	complex water infiltration	9	11.5	17	23.0	10.0	1.16	0.18	–30	16.7	21.0 ÷ 24.7
12	LANCKORONA	gray slate, sandstones (15%) fold disorders	complex water infiltration	8	12.0	12	22.7	15.0	1.16	0.18	–30	16.4	20.0 ÷ 38.6

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Table 3 [cont.]

No.	Landslide	Lithology and tectonics	Slide type and cause	Landslide slope			*KFG* class [points]	Refraction boundary [m]	Correction coefficients			SMR class [points]	Range of KFG changes [points]
				Dip [°]	Slide surface [m]	Slide size [mm]			F_1	F_2	F_3		
13	NOWE RYBIE Folwark	shales, variegated shales, sandstones (10%) overlap, close to fault zone	complex water infiltration	10	4.5	136	21.2	5.0	1.16	0.19	–30	14.6	20.4 ÷ 21.5
14	LELUCHÓW	sharp slates, sandstones (35%) fold disorders	complex water infiltration load.	18	9.5	Pipe rupture	25.1	10.0	1.16	0.24	–30	16.7	21.6 ÷ 29.3
15	ZRĘCZYCE	Slates, margl, sandstones (~10%) overlap area	complex water infiltration	7	4.0	7	19.6	3.5	1.16	0.18	–30	13.3	19.6 ÷ 20.5

The studied landslides, like most of the Carpathian structural-weather landslides, are extensive landslides, usually over 100 meters long and wide, and with a slip surface usually located at a depth of several to several meters. It can be assumed that on the scale of the entire slope such landslides are characterized by a flat slip surface, approximately parallel to the slope inclination the slope extension lines and slip surfaces are approximately parallel. The values of the correction coefficients given in the table were determined for such averages for the entire slope, the angles of fall and the extent, and that of the terrain surface as well as the slide surface. The value of the *SMR* slope stability class determined on their basis is therefore the average value for the entire slope. Locally, both the ground surface and the slip surface may not meet this assumption to a greater or lesser extent. In the case of variable slope angles and/or slip surfaces, as well as variable values of the *KFG* geotechnical class of the material building the slope, the *SMR* stability class of the slope within the slope will also be variable. The probability of a slope inclination characterized by variable activity will depend on the probability of a slope of its individual fragments.

The results of the tests presented in Table 3 indicate, in accordance with the reality, that for all the analyzed measurement points located on active landslides composed of shale flysch, the value of the *SMR* classification number is lower than 20, which indicates very unstable slopes (stability class V) likelihood of sliding greater than 90%. The compliance of the actual state of stability of the above-mentioned slopes with the forecast justifies the use of the *SMR* classification to assess the stability of flysch slopes.

All slopes included in the table are made of shale flysch with a sandstone content of 10-35%. This confirms the results of previous studies and observations indicating that slopes made of weather-prone shale flysch are particularly prone to loss of stability. The value of the geotechnical class *KFG* and the stability class *SMR* determined on its basis varies within individual slopes, which is consistent with the results of inclinometric measurements and field observations. From the landslides listed in Table 3, high variability of landslide activity is characterized, for example, by the ŻEGOCINA landslide (Fig. 3), where the *KFG* class value varies from 22.7 to 33.5, and the ZRĘCZYCE landslide low variability, where the value of the *KFG* class, ranging from 19.6 to 20.5, is practically constant.

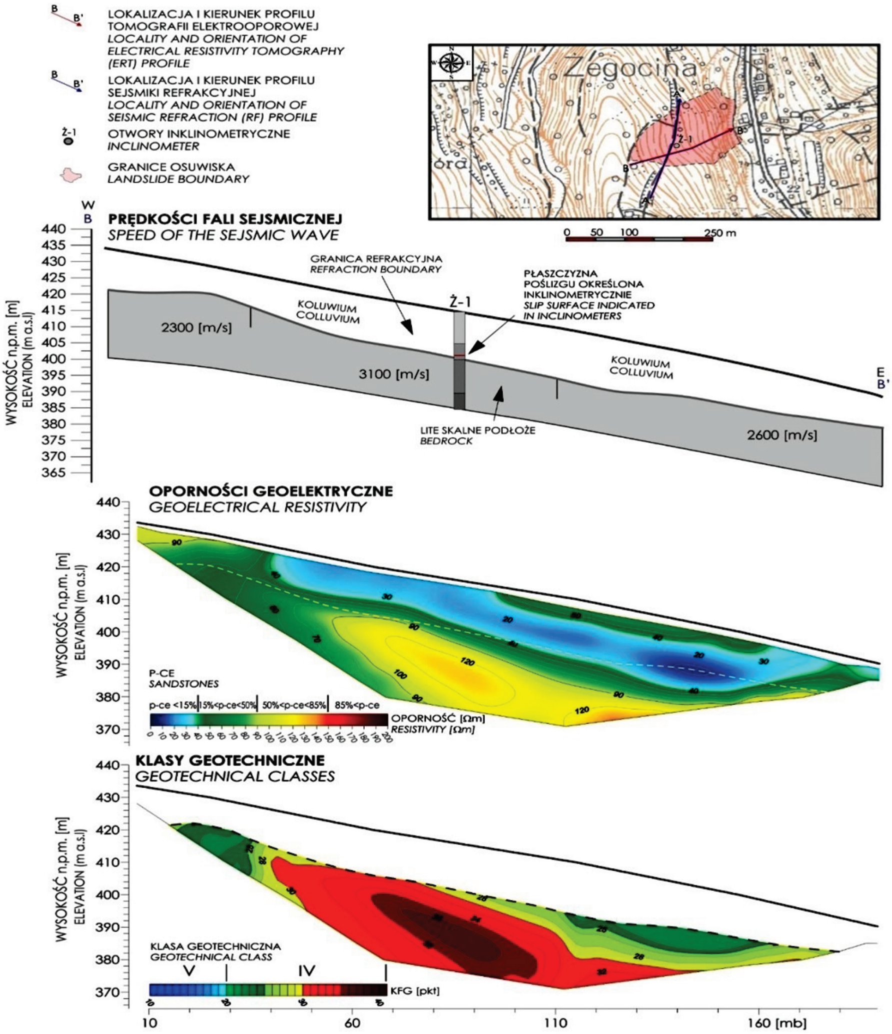

Fig. 3. The slope with a large variability of slide susceptibility. Żegocina Lanslide – geophysical tests results along B–B' profile

The likelihood of a slope inclination characterized by variable activity is a function of the likelihood of a slide of its individual fragments. Information on the variation in landslide activity within the slope, determined on the basis of the *SMR* classification, may therefore be helpful in determining the output data for the accurate calculation check of the slope stability to check the forecast. The knowledge of the differentiation of the *SMR* class within the slope allows for the optimal location of the boreholes to determine the parameters of the material from the slip zone, and the refractive limit determines the location of the potential slip surface, which is necessary to perform the computational stability analysis.

A particularly important issue is the reliable assessment of the slope stability in the areas of the foundation of hydrotechnical structures [10]. In recent years, after catastrophic rainfall, especially in 2010, landslides have become active in the immediate vicinity of such structures, e.g. a landslide in the area of the right abutment of the dam in Czchów or a landslide on the slope of Mount Żar, near the right abutment of the dam in Porąbka. During the construction of the Świnna Poręba dam, the above-described landslide was activated in the area of the hydrotechnical tunnel inlets, stabilized by means of anchoring. Recently, the stability of the slope adjacent to the right wing of the Solina dam has also been tested.

Of the recently activated tens of thousands of landslides in the flysch Carpathians, many are located in the coastal zones of artificial water reservoirs, including several in the areas of the abutments of the existing front dams, which may endanger their safe operation. Therefore, it is advisable to pay special attention to the stability of the slopes in the area of the abutments of the existing dams and, in case of any doubts, perform a stability analysis for them using the *SMR* method, and in the case of an unfavorable forecast, perform a detailed calculation analysis of the stability and, if necessary, take stabilizing measures.

5. Summary

Geological and geophysical studies of Carpathian landslide slopes in the coastal zones of artificial water reservoirs and active landslides, studied under the SOPO program, enabled the development of an optimal methodology of geophysical studies of Carpathian landslide slopes. Measurements of the seismic refraction profiling and electroresistivity profiling allow to determine the geometry of the landslide (vertical and horizontal range and the course of the slip surface) necessary for the computational analysis of the slope stability. Based on the velocity of seismic waves, it is also possible to estimate the susceptibility of slopes to mass movements. Seismic and electroresistivity tests make it possible to determine the geotechnical class *KFG* of flysch, on the basis of which, using the *SMR* proposed by M. Romana, it is possible to quickly quantify the stability of flysch landslide slopes. Examples of tests and evaluation of the stability of active landslide slopes based on this classification are summarized in Table 3.

Due to the high susceptibility of flysch slopes to mass movements, it is advisable to pay attention to the slope stability in the edge zones of artificial water reservoirs, especially in the areas of abutments of front dams.

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Badania geofizyczne i wykorzystanie ich wyników w ocenie stateczności zboczy sztucznych zbiorników wodnych w Karpatach fliszowych

Słowa kluczowe: geofizyka, hydrotechnika, osuwiska

Streszczenie:

W artykule przedstawiono możliwość wykorzystania badań geofizycznych w ocenie stateczności zboczy karpackich zbudowanych z podatnych na ruchy masowe utworów fliszowych. Szczególnie podatne na utratę stateczności, z powodu erozji strefy brzegowej i zmiennego poziomu wody w zbiorniku, są zbocza osuwiskowe położone w strefie brzegowej sztucznych zbiorników wodnych. Badania geofizyczne osuwisk wykonane w ramach programów badawczych PR-7, realizowanego przez IMGW w latach 1972–1980 i SOPO, realizowanego przez PIG w latach 2009–2016, umożliwiły wypracowanie metodyki badań geofizycznych umożliwiających określenie geometrii (przebieg powierzchni poślizgu i poziomy zasięg) istniejących osuwisk, informacji niezbędnej do przeprowadzenia analizy obliczeniowej ich stateczności. Przedstawiono przykłady rozpoznania geometrii osuwisk w strefie brzegowej zbiornika Czorsztyn oraz osuwisk w rejonie sztolni hydrotechnicznych zapory Świnna-Poręba. Przedstawiono również możliwość ilościowej oceny stateczności zboczy karpackich na podstawie klasyfikacji *SMR (Slope Mass Rating*) zaproponowanej przez M. Romanę, wykorzystując do oceny masywu klasyfikację geofizyczną *KFG (Klasyfikacja Fliszu – Geofizyczna)* równoważną z klasyfikacją *RMR (Rock Mass Rating)* Z.T. Bieniawskiego. Zestawiono kilkanaście czynnych osuwisk, dla których określono stateczność metodą *SMR*.

Received: 19.08.2021, Revised: 15.09.2021