Human-induced landslides in the Angren coal district, Uzbekistan

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Abstract: The authors of this paper wish to acquaint the Czech and Slovak professional landslide expert public with the issues of slope deformations in the post-Soviet republics in Central Asia. As an example, two sites were chosen in the vicinity of the town of Angren in Uzbekistan. The main part of this paper deals with human-induced landslides which were caused by mining activity in the "Razrez Angrensky" bituminous coal pit ten kilometres east of the town of Angren. It is an area in which slope deformations are known as being of natural as well as anthropogenic origin. It often occurs that an old, stabilised landslide is activated by deepening a coal pit. As examples, we have chosen two landslides called "Atci" and "Staraya Podstanciya". Both the slope deformations were set in motion by work in the bituminous coal deposit of Jurassic age, but the cause proper was different. In the "Atci" slope deformation, it was the gasification of a coal seam on the adjacent southern slopes of the River Angren, whereas the "Staraya Podstanciya" slope deformation was set in motion by mining activity proper on the northern wall of the opencast pit. The great majority of survey and monitoring work was carried out by Uzbek specialists; the Czech researchers at these sites tested some of the methods which could be considered as novelties at the time of their application. Another activity of the Czech party included cooperation in the interpretation of geophysical measurements, not only conventional geophysical, but also engineering-geological. Czech-Uzbek cooperation has been taking place since 1981 and it can be pointed out that three generations of specialists of both the parties have already participated in the solution of the problems of slope deformations. One of their outputs was also the book "Modern methods for measuring stress and pore pressure and landslide motion at depth".

Key words: slope deformation, human-induced landslide, Angren, geoacoustics, radar interferometry, monitoring

1. INTRODUCTION

Slope deformations caused by human activity, "human-induced landslides", whether caused by the construction and operation of roads and railways, or by mining, valley reservoirs and other human activity in Uzbekistan, annually account for 50 –70% of their overall number (Niyazov, 1982; Niyazov, 2015; Niyazov et al., 2015). The risk of such slope processes is characterised by an unexpected beginning of movement, by frequent recurrence, by a long duration of development and by the cycling character of movement. The Angren coal pit has been developing since 1947. In 1952, the designed capacity of 1.5 million tonnes of coal was achieved for the first time and in 1975, 4.5 million tonnes were mined every year; the area of the pit was 5.5 km^2, its depth being 200 m. In 2000, its depth was 300 m and in 2012, its maximum depth was 405 m, with its area being 20.2 km^2. In the future, the depth of the pit will increase down to 520 m. The area will extend to 30 km^2. Since 2012, the "Angrensky coal pit" has had these mining and technical parameters: it is 3.6–4.8 km long and 2.0–3.3 km wide. The height of the working benches is 6–15 m, the width of the working platform on the benches is 20–35 m, and the number of the benches is 15. Since 2019, the outer boundaries of the section have not much changed. The height of the working benches is 8–15 m, the width of the working platform is 30–70 m, and the number of the benches is 9. The mining benches shifted deeper by 200 m or less from 2011 to 2019, and on the northern side up to 60 m. The mining and technical parameters of the working slopes (bench faces) have not corresponded with the designed parameters for more than 25 years; the height and steepness of the working benches is overrated. For several years, the stripping work has lagged, which caused a long-time standing of the walls and a change in the structure of groundwater runoff. Over time, suffosion processes have increased in the depth of the rock mass as well as in the frequent occurrence of landslide processes associated with them. Landslide processes of a different scope have always been taking place there and will occur in the future as well (Syrovatko, 1956; Niyazov et al. 1989, 2002).

Similar problems can be encountered in the areas of brown coal mines opencast mining in Slovakia and the Czech Republic. In Slovakia, there are problems with the stability of slope deformations in the vicinity of "Handlová" and "Nováky", while in the Czech Republic, the stability of high slopes in the area "Mostecko" was monitored during brown coal mining. Thanks to this, Czech and Slovak geophysicists have experience in solving such problems (Bláha P., 1993, 1996).

For the future, the main mining of coal is planned on the south-western working sides of extraction. In the period of 2011–2019, in the "Razrez Angrensky" coal pit, the staff of the State Landslide Service recorded 14 great landslides of a volume of more than 100 000 m^3 and several tens of cracks and minor soil landslides (Fig 1).

The geological structure of the site is represented by a thick layer of Quaternary gravels (up to 70 m thick), Palaeogene silty sands, plastic clays, and sandstones (up to 35 m), Neogene clays, sandy marlstones, and limestones (up to 30 m). Kaolin clays, siltstones and sandstones are 25 m thick or less, while the coal production bed is up to 70 m thick. Landslides occur in the contact zone of

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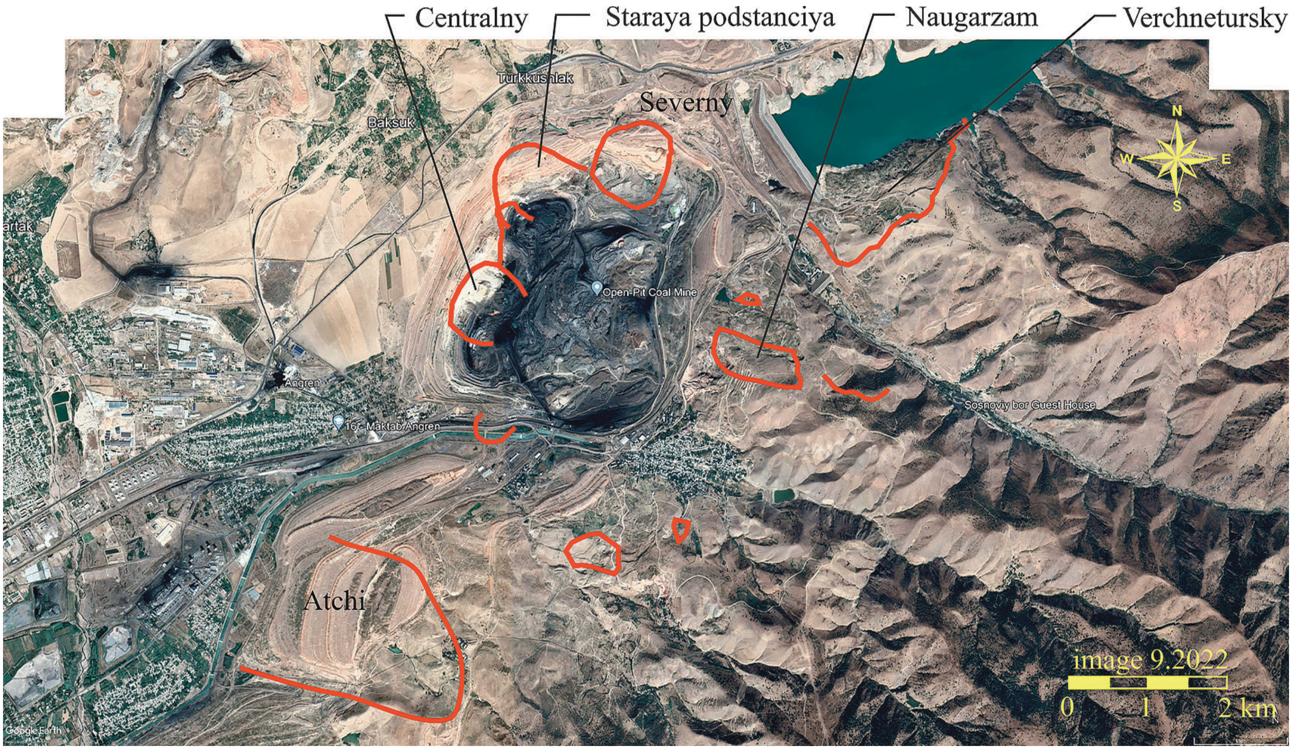


Fig. 1: Slope failures around the "Razrez Angrensky" coal pit

the Alai limestones with sandstones and clays of Suzak sediments (Fig. 2). The Alai Stage contains limestones 10–30 m thick, stiff, with 15.8 % porosity and 20.7 MPa strength. The rocks have low water content (3.4 %). They are not water-absorbing, are relatively

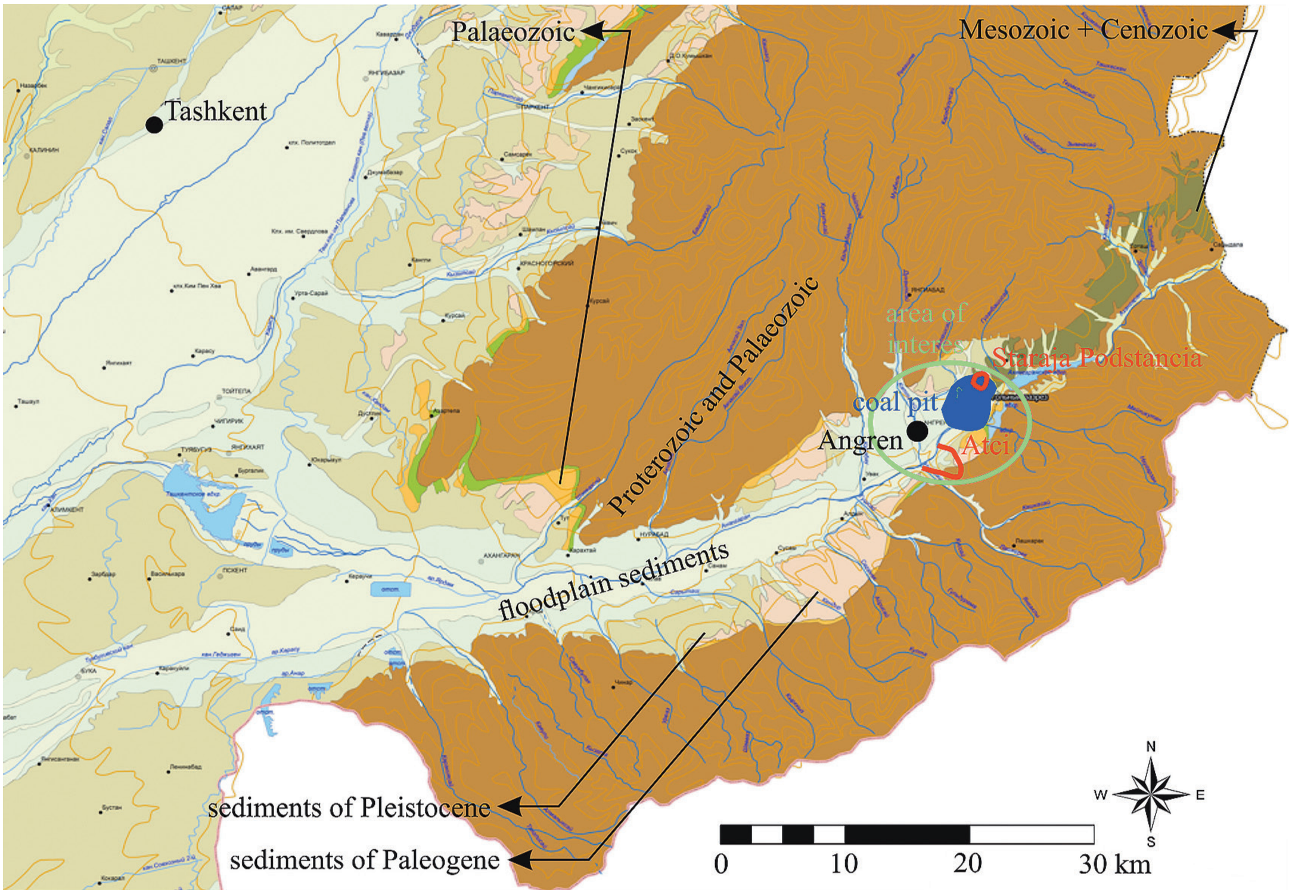
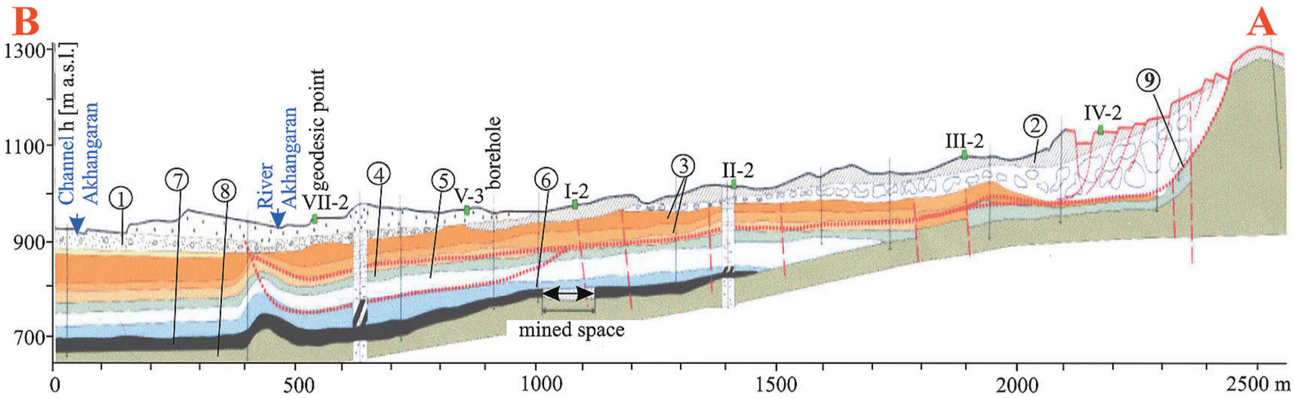


Fig. 2: Geological map of the area

stable and moderately weathered. The Suzak Stage is 10–40 m thick, composed of sandstones, gravel clays and conglomerates with sandy-marly clays (Fig. 3). The hydrogeological conditions in the Angren coal pit are distinguished by four groundwater-bodies: Quaternary, Cretaceous-Palaeogene, Jurassic and Palaeozoic. The rock mass is fed by atmospheric precipitation, surface runoff from wadis and infiltration through tectonic zones. The intensity of rock waterlogging and the occurrence of groundwater lead to the relatively broad development of landslide processes. The possibility of drainage of layers is determined by the fact that the depression curve has a steep character and lies in the immediate proximity to the surface of the pit wall.



1-alluvial gravels; 2-loess loams; 3-paleogene marls, Alai limestone; 4-Suzak sandstones, sands, clays; 5-Cretaceous conglomerates, sandstones, clays; 6-Jurassic clays and sandstones; 7-coal; 8-siliceous porphyries; 9-shear plane, VII-2, V-3, I-2, II-2, III-2, IV-2 boreholes

Fig. 3: Geological cross-section through the left slope of the "Akhangaran" (profile location see Fig. 6)

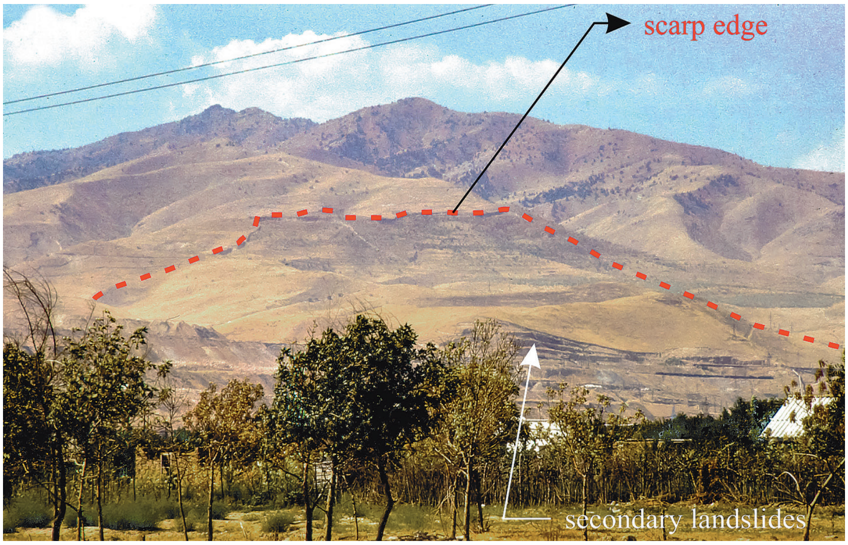


Fig. 4: "Atchi" slope failure

2. RESULTS AND DISCUSSION

2.1. "Atci" Slope deformation

The first slope deformation, which we worked together on, was the "Atci"landslide, which is located on the southern slopes of the "Akhangaran River" (Fig. 4, Fig. 5) The landslide occurred just on the slope affected by gasification and subsequently began to threaten the operation of the opencast pit proper (Bláha P. et al. 2023). The landslide having 8 km^2 in area and 800 million m^3 (Mm^3) in volume had its shear plane at a depth down to 140 metres (Fig. 6). The first trigger to the origin of the landslide was, as already given before, the gasification of a coal seam 5–15 metres thick at a depth of 100–130 metres with an area of 1.2 km^2. A view of a part of the landslide with "extraction boreholes" and gas piping is in Fig. 5. The first movements were detected in March 1971.

Fig. 5: View of "extraction boreholes" and gas piping

The determination of the depth of the shear plane was very difficult, which arose from both its great depth and the

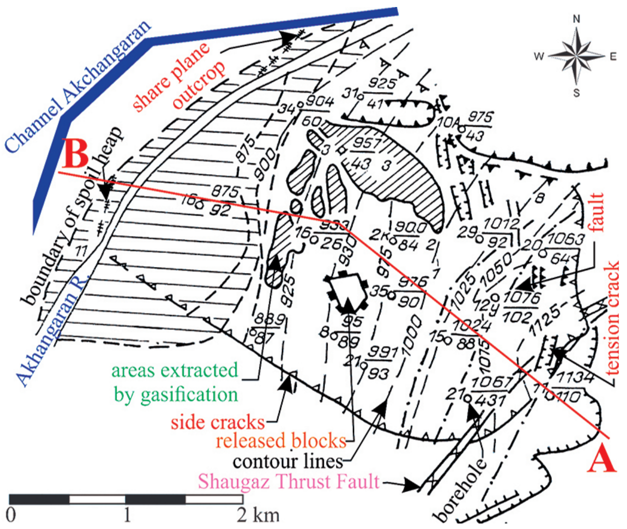


Fig. 6: Map of the "Atchi" slope failure

complicated geological structure of the investigated area. In the engineering-geological survey of this slope deformation, geophysical methods were also used, both ground-based and drilling. The ground-based methods included resistivity methods and the method of spontaneous polarisation. The down-hole logging methods comprised only the methods available in Uzbekistan at that time, i.e. the method of natural gamma radiation, the resistivity methods (potential probe and micro logging) and the measurement of the borehole diameter. The analysis of each curve has shown that it is possible according to the drop in apparent resistivity and the reduction of the borehole diameter to measure zones in which the rock mass is being fractured (Fig. 7).

The movement of the landslide was monitored using surface-based and deep marks by investigating the deflection of the borehole using templates (precise inclinometry was not available at that time). Over the first four years, the deformation of the slope reached up to two metres and the velocity of movement up to 50 mm per day. In addition, the fluctuation of groundwater level was measured as well as pore water pressure.

The Czech geophysicists carried out geoacoustic measurement in a borehole (borehole depth – 50 m, drilled 1982) which was prepared by the Uzbek party. The drilled borehole was fitted with plastic casings and the space between the borehole wall and the casing was filled with clay-cement slurry. The methodology of geoacoustic measurements was the same as used in Czechoslovakia. After the first installation of eight sensors in the borehole, a resting time was left in the duration of 12 hours (Bláha, 1996). The resting period after relocation of geophones was 60 minutes, the same as the time of measurement. The borehole could be measured only from 21 metres down because the drilling crew was not able to seal sufficiently the casing string. The evaluation of geoacoustic measurements in the form of the frequency of pulses showed that the rock mass was stressed 28 to 34 metres around the borehole while it began to be fractured at a depth of 30 metres (Fig. 8). If we compare this depth with the first two

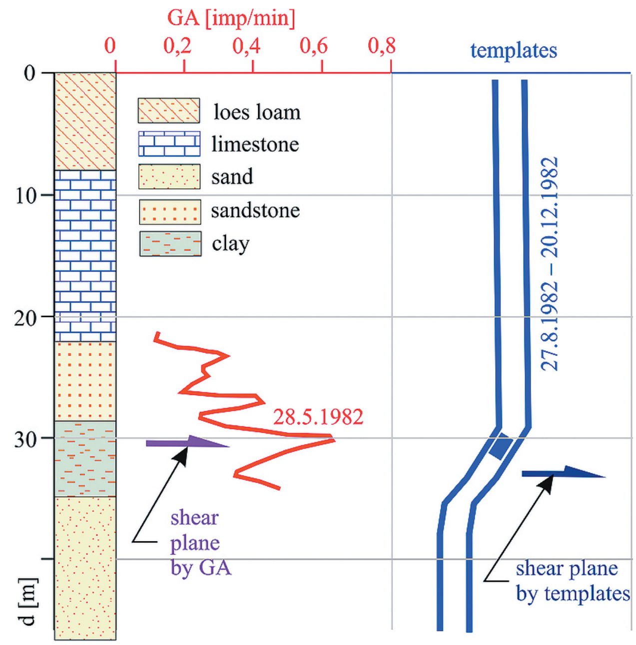


Fig. 8: Results of geoacoustic measurements

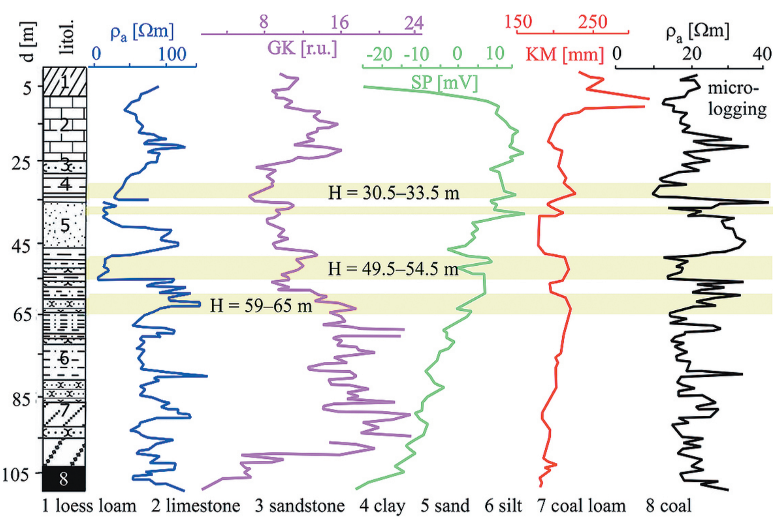


Fig. 7: Down-hole logging on the "Atchi" landslide

zones of fracturing from down-hole logging, then we must state that a good agreement of indirect methods in assessing the state of the rock mass. The time showed that the fracturing of the borehole predicted from geoacoustic measurements had been justified. The borehole was cut by slope movement at this depth in about seven months according to the measurement of the passability of the borehole.

The shear plane of the landslide and its position were determined by monitoring the damage to the casing of 70 boreholes and it was stated that its longitudinal inclination was 6–8° and the transverse inclination 5–7° towards the west. In the upper part of the landslide, several partial shear planes were determined. In different parts of the landslide, these planes correspond to different geological boundaries (e.g. the base of loess). The position of the scarp edge of the landslide relates to the Shaugaz Thrust Fault (see Fig. 6).

The landslide was remediated by placing a counterweight fill at the base of the slope, which also functioned as the outer spoil bank of the bituminous coal pit. The time pattern of deformations, the velocities of the landslide and the volume of the counterweight fill is depicted in Fig. 9. The figure describes the development of the landslide during more than 55 years. The highest velocity of movement was recorded in the years 1967 to 1982, with the highest maximum being registered in the years 1975 and 1976. Another significant acceleration was measured in the years 1987, 1994–1996, 2002 and 2009. These periods of time always correspond with the increase in overall deformation. The total volume of the counterweight fill, the outer spoil bank today, corresponds to 230 Mm^3.

2.2. "Staraya Podstanciya" Slope deformation

The second slope deformation, on which the Czech party has made a greater mark, is the "Staraya Podstanciya" landslide (beginning of movement 2008). It is one of several landslides which originated on the northern and north-western walls of the bituminous coal pit. All landslides surrounding the pit are depicted on a satellite image (Fig. 1). There are also other minor slope deformations which occurred in places where they did not threaten anything, and, therefore, greater attention was not given to them. However, these slope deformations were also monitored by the State Landslide Service (Fig. 1, Fig. 11). In such a case, slope deformations are monitored only by occasional field traverses of a responsible geologist without using any technical devices of monitoring. The main landslides which are monitored in the above-mentioned places of the pit are depicted with names in Fig. 10. Fig. 11 shows a conventional map of such landslides.

In the period of 2008 to 2011, at this site, we tested possibilities of using radar interferometry (Abdullaev et al., 2013). Unfortunately, the test measurements, which showed possibilities of using this method also in this area, did not turn into the implementation of the planned project.

Since the early 1980s, new landslides have begun to appear on the walls of the giant opencast pit. According to the Uzbek engineering geologists and specialists in the study of earthquakes, it relatively often happens that the last trigger to the initiation of landslide movement is the effect of the remote Hindu Kush earthquakes (distance "Atci" - Hindu Kushz = 550 km). They have their epicentres at depths of 100–200 km, their frequency is 2.5 Hz or less and their duration is over 120 seconds. The largest of the landslides, "Staraya Podstanciya", appeared, as already mentioned, on the northern wall of the pit. At the beginning of its existence, the length of the landslide was 750 m, its volume 58 million m^3 and the velocity of movement 20–24 mm/day. The

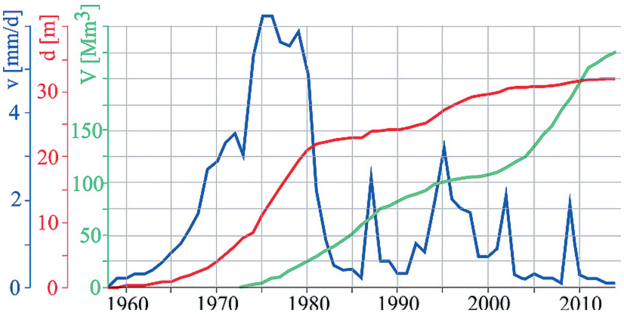


Fig. 9: Pattern of deformations, velocities of movement and volume of counterweight fill on the "Atchi" landslide ?? Fig. 9 Slope failures around the "Razrez Angrensky" coal pit

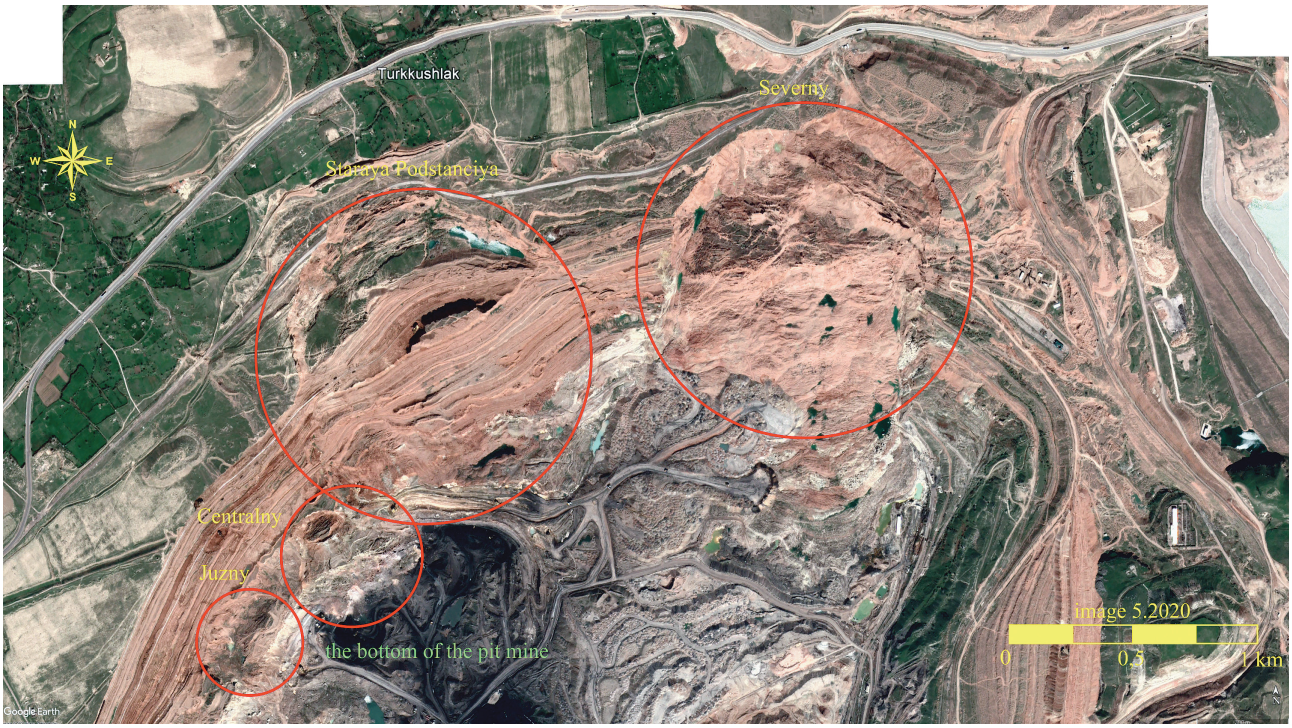


Fig. 10: Slope failures on the north and northwest walls of the pit

dimensions of the landslide changed not only by its own movement, but also by mining activity, due to which its toe had been excavated. Around the year 2010, the landslide increased and absorbed minor surrounding landslides. In that year, the length of the scarp crack has a value of 1400 m and the landslide was 900 m long at that time, having an average thickness of 100 m and a volume of 120 million m^3. The highest velocities of movement reached up to 750 mm per day. Gradually, the velocity of the landslide decreased to 45 mm/day and the overall movement per the year 2011 reached 100 m horizontally and the vertical drop 50 m. At the time of a visit of Czech specialists in 2012, the tension scarp crack was about 200 m wide and the drop of the ground in the crack about 40 metres (Fig.12).

Figure 12 shows photographs of different stages of the development of the "Staraya Podstanciya" slope deformation. The size of this slope deformation may best document the size of the tension crack, which is well evident on two upper photographs. It was perhaps most surprising for the Czech geophysicist on this landslide that the lake (Fig. 12, the second photograph from below) was never pumped out, never drained in any period of his visits at the site! On the last photograph, there is an example of disintegration of the displaced blocks of the landslide. Some blocks break down in such a way that their surface remains flat while other blocks break down into narrow pyramids or even needles.

Engineering-geological, geodetic, and geophysical work continues at the site until today, even if it is necessary to say objectively that the interval between measurements has changed fairly significantly during monitoring of the landslide. More on the geophysical measurement can be found at the article published in the EGRSE journal (Bláha et al., 2023).

Interesting findings in this region were shown by the method of radar interferometry. From a foreign grant we were able to carry out a series of evaluation of radar images obtained from a period between 11 July and 15 August 2009. Their most important result is Anomaly 1, which is on the left side of Figure 13, marked with a violet oval (Bláha et al., 2023). Over a period of time of about 35 days between individual measurements, deformation there reached a size of about 2.5 mm. At the time just after measurements, neither the radar specialists nor Uzbek or Czech geophysicists found any explanation for this anomaly. This was manifested only on 21 March 2011, when the "Staraya Podstanciya" slope deformation set in motion. Anomaly 1 can then be deemed as a precursor of movements, which were visible to the naked eye only after 550 days. Anomalies 2, 3 and 4 are signs of settlement of the berm on the "Atci" landslide. Anomaly 5 is a sign of movements in the "Verchneturskу landslide" (Fig. 13). It does not reach very high values and does not pose a risk to the "Akhangaranskaja plotina" ("Akhangaran Reservoir") proper. Anomaly 6 is a typical radar image of a more extensive water surface. Anomalies 7 and 8 indicate changes in the coal pit proper. Finally, Anomaly 9 is an image of the Naugarzam landslide, which lies east of the pit, but does not threaten its operation in any way.

Still one fact is interesting. It is not unusual that minor landslides subsequently originate on side cracks of large slope deformations. There, an opposite feature occurred. In 2011, in fact, a side crack of the "Staraya Podstanciya" slope deformation was created from the minor "Centralny" landslide formed in 1985.

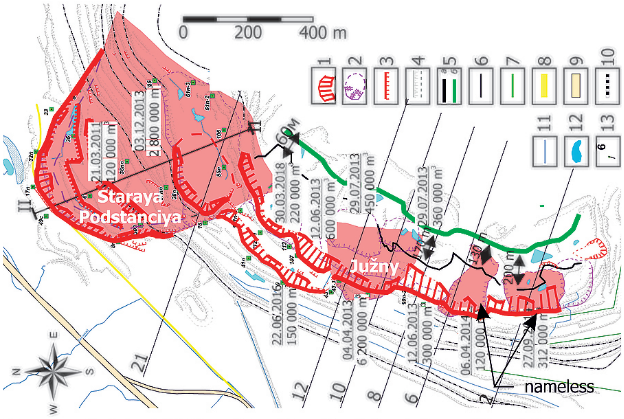


Fig. 11: Map of slope deformations on the north and northwest walls of the pit

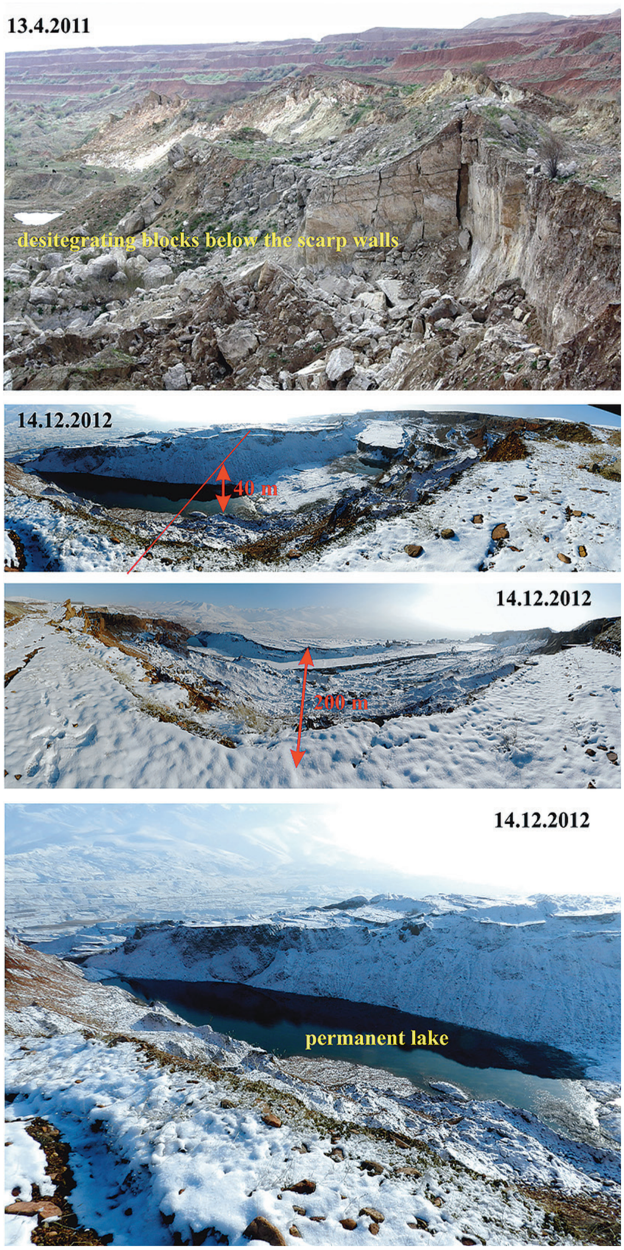


Fig. 12: Photographs of the "Staraya Podstanciya" landslide

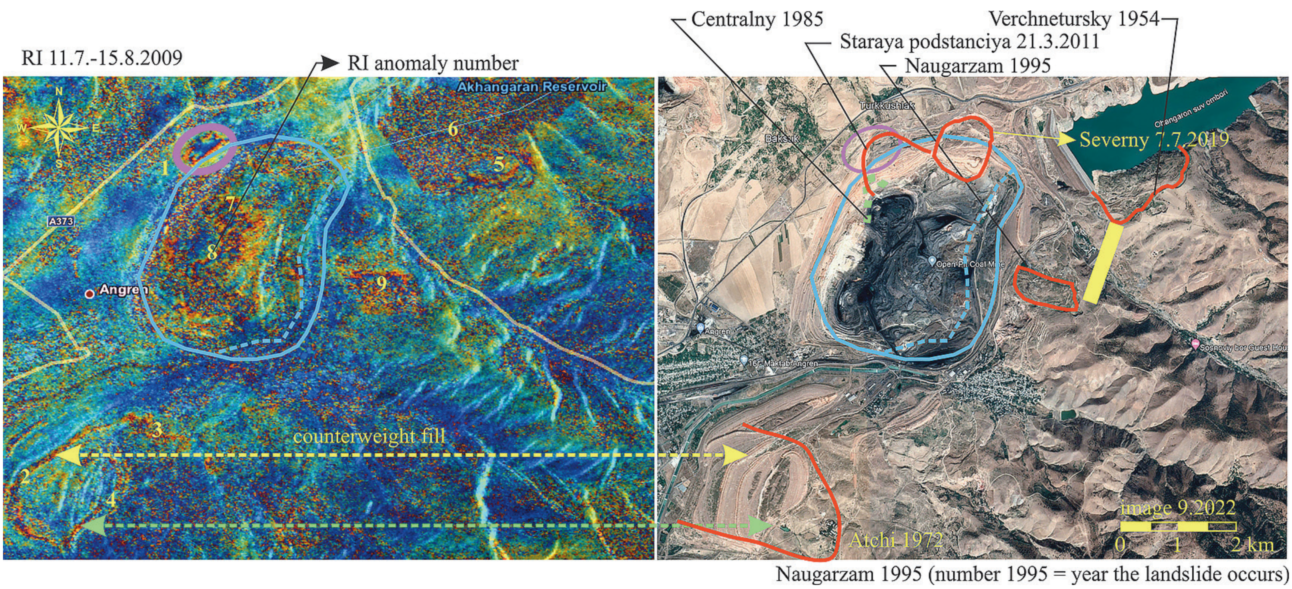


Fig. 13: Anomalies of deformations in the vicinity of the mine determined by radar interferometry

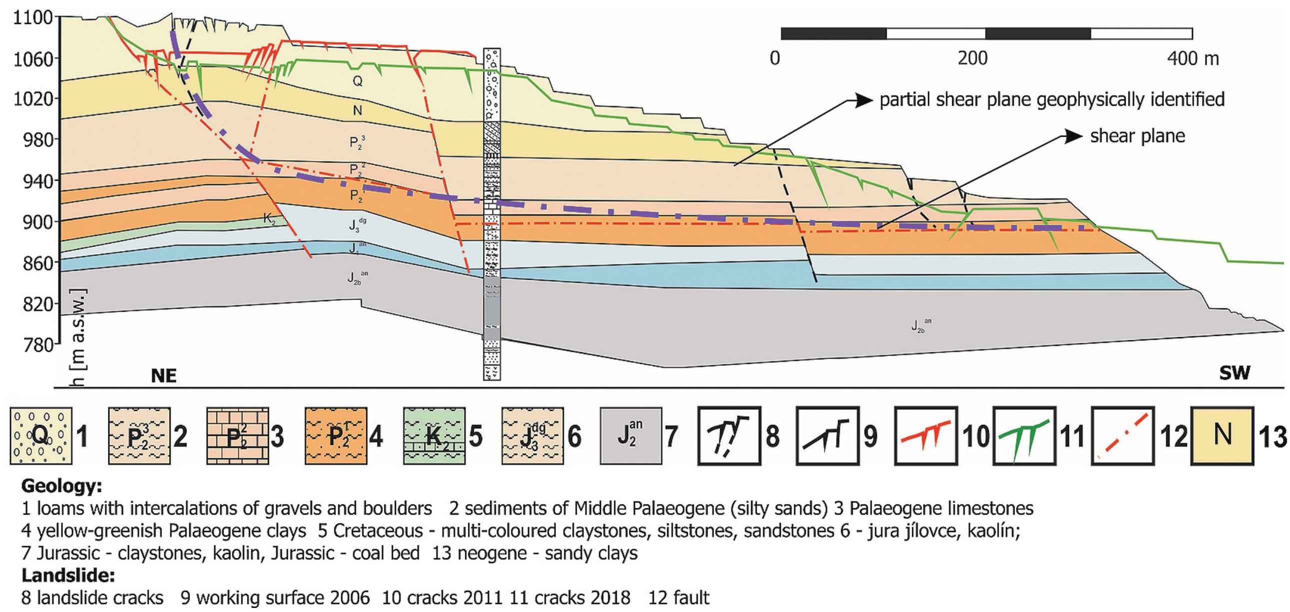


Fig. 14: Geological cross-section through the „Staraya Podstanciya“ landslide (profile location see Fig. 17)

On more recent satellite images, it is now difficult to identify the "Centralny" landslide.

Fig. 14 shows a geological cross-section through the landslide. Based on the investigation by Uzbek engineering geologists, shear planes mostly "remain" in younger rocks; they are found in the rocks of Jurassic age only rarely. Fig. 15 shows the latest satellite image of the "Staraya Podstanciya" landslide. The image is dated 2 May 2023.

Fig. 16 depicts horizontal (in blue) and vertical (in red) deformations and the velocities of sliding of three points of the "Staraya Podstanciya" landslide. Below the pattern of each parameter, the positions of points 6, 35 and 5303 (Fig. 17) are depicted in the underprint along with the contour of the landslide. Points 5303 and 35 lie at the left and right-side crack, respectively, point 6 then in the centre of the landslide. By observing all curves, it can be found that no significant differences exist between the movements of such points. It is clear that the greatest movements were just after the initial movement of the landslide. Then a period of resting followed, namely until the beginning of the year 2017 when the size of movement of the landslide again increased. Its cause was, in most likelihood, more extensive mining and preparatory work in the pit. Interesting is the movement of point 5303 in 2010. While the whole future landslide was not deformed in that year, point 5303 moved. Here, it is necessary to realise that in fact this point already lay on the moving landslide which was the "Centralny" landslide.

3. CONCLUSION

The submitted paper shows to the Slovak and Czech landslide experts the issue of landslides, the movement of which was caused by human activity. The area surrounding the "Razrez Angrensky"

Fig. 15: Satellite image of the „Staraja Podstanciya“ landslide. This image is dated May 2, 2023.

coal pit was taken as an example, namely the largest two of them. The first landslide, "Atci", occurred with the contribution of gasification of underlying bituminous coal. This landslide has been monitored by Uzbek specialists for 65 years. The second landslide, "Staraya Podstanciya", occurred on the side wall of the giant opencast pit mentioned above.

The entire activity in monitoring the landslides induced by anthropogenic activity in the Angren coal area was based on the initial engineering-geological traverses conducted immediately after the slope movement had been identified. Both the landslides concerned slope deformations of a large extent, in which it was obvious from the first traverses that it was not practically possible to stabilize them in a fast and simple way. For this reason, an engineering-geological map of landslides was compiled and subsequently monitoring networks were installed. Shortly after the formation of the "Atci" landslide, this concerned a network of geodetically monitored points together with the use of simple methods monitoring the changes of the shape of the plastic casings of boreholes. The surface mapping of the landslide was complemented by geophysical measurement, largely by geoelectrical methods and down-hole logging in selected boreholes. From this system of landslide behaviour monitoring, it was possible to propose a system of work in the opencast coal pit so that its safe operation was ensured.

In the 1980s, measurement in boreholes was complemented by geoacoustic measurement, which showed the disturbance of the rock mass at depths of more than 29 metres. A borehole was drilled down to 50 metres, but it was passable for the sensing system only down to 35 metres at the time of geoacoustic measurement. The monitoring measurements showed that the use of outer spoil bank as counterweight fill at the base of the landslide had decreased sliding to 10% of the original values. The velocity of movement in time-limited sections had increased for a short time, but never to the original level.

The "Staraya Podstanciya" landslide was monitored in a similar way as the "Atci" landslide adding that when monitoring the slope deformation, satellite images were already used, and the method of radar interferometry was applied occasionally. The latter showed minimum movements behind the edge of the giant opencast pit in places in which the main scarp of the large landslide was formed in two years.

The size of the described slope deformations and their movements are unusual for the situation in Central Europe. It is necessary to point out that the possibilities of the use of the new methods of survey and monitoring of slope deformations in Central Asia had been very limited in the years 1970 to 2015. However, this fact cannot be attributed to the reluctance of the local specialists to apply new methods, but this reality was governed by objective possibilities in those times. Nowadays, it can be stated that the equipment of the workplaces there has already achieved the common level of operating organisations. Despite this objective limitation it is necessary to state that the local specialists have

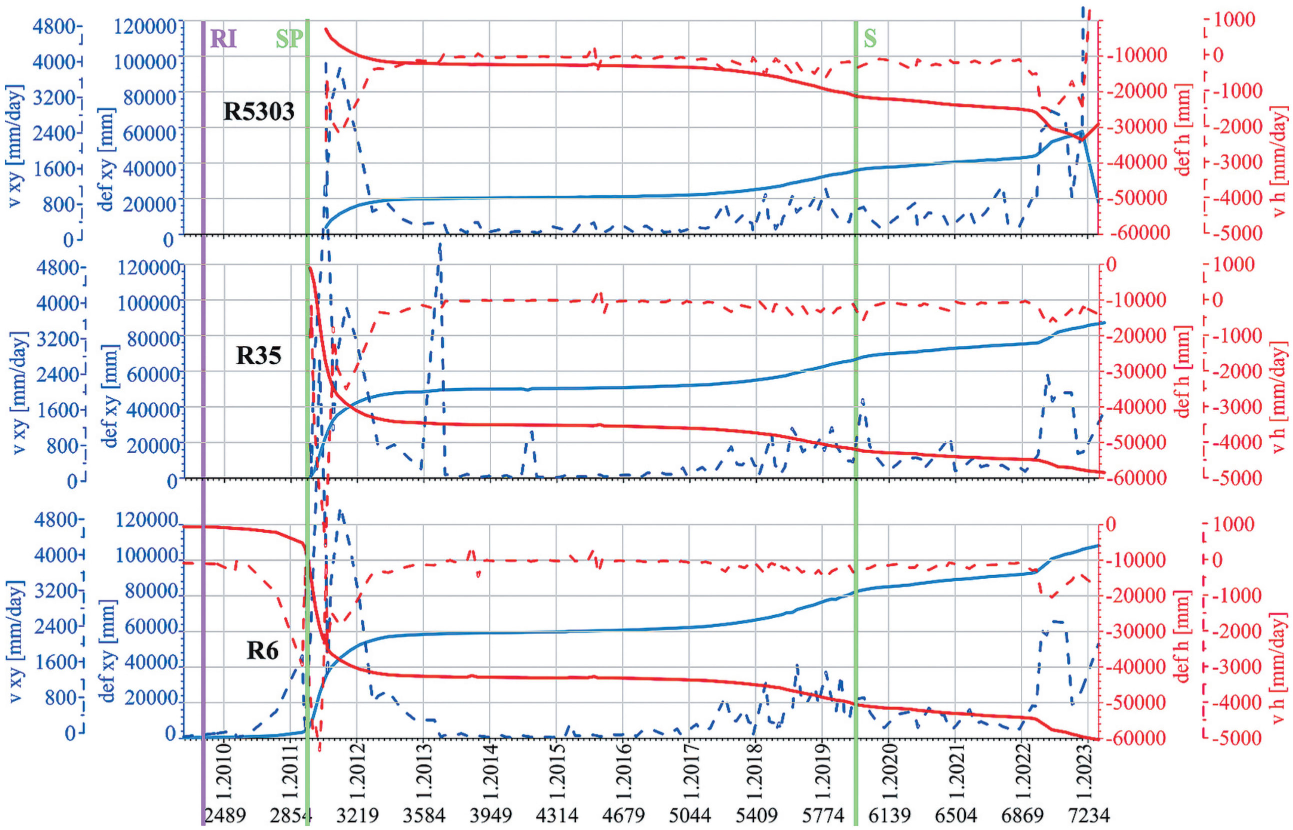


Fig. 16: Results of geodetic measurements (deformation and speed of movement) of selected points on the „Staraya Podstanciya" landslide (geodetic points see Fig. 5)

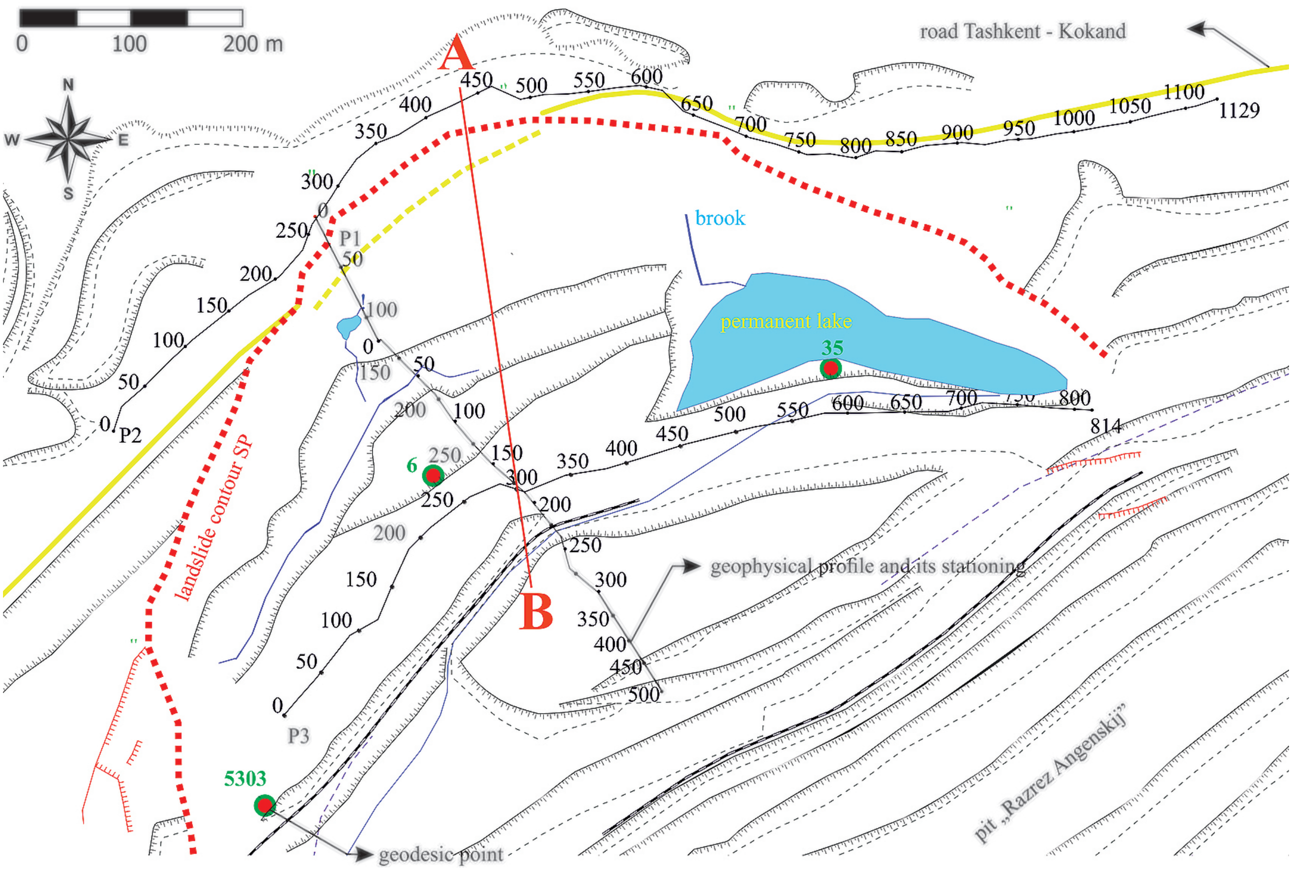


Fig. 17: Situation of geodetic points and geophysical profiles on Staraya Podstanciya landslide

managed to ensure the safety of the operation of coal pits at a high level and that no events which would claim human casualties or the health of miners during their operation have occurred.

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