THE USOY DAM AND GEOPHYSICAL MEASUREMENTS

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1. Introduction

Man cannot live without water and there is no life without water. Astonishing works were built as early as the prehistoric times of human civilization. Even in modern time, we admire Iranian qanats, Roman aqueducts and other hydraulic structures of ancient times and the Middle Ages. Modern techniques have enabled works totally surpassing the visions of older generations to be built. Let us mention the highest completed dam in the world at Nurek in Tajikistan, the largest hydroelectric plant Three Gorges in China and also the longest dam in the world – Hirakud in India. Yet, the highest dam in the world was not built by man, but created by nature itself.

A hundred years ago, during an earthquake in Tajikistan, a rock-fall took place, burying the village of Usoy and damming the River Murgab. Behind the newly formed dam 650 meters high, a lake has been created over years, having a volume of about 17 km^3 and a length of 60 km. Seepage through the dam poses a great risk. The opening of this seepage is now at a distance of only 1,500 meters from the water surface in the dam lake. Because the dam is natural, this seepage is uncontrollable and, together with head erosion, poses the highest risk to this creation of nature.

Another risk at Sarez Lake is posed by slope deformations. The most serious situation is with the so-called right-bank landslide lying in close proximity to the "right-bank¨ keying of the dam. A rapid movement of the landslide that may pass into falling could trigger a wave which would overtop the dam crest and could cause its stronger erosion. The other slope deformations do not pose such a threat, especially because the vicinity of Lake Sarez is practically an uninhabited area.

2. The Results of Geophysical Work that Was Carried Out

Survey work in the area of the Usoy dam and Lake Sarez is very difficult. Obstacles are climatic conditions, impassability of the terrain and its difficult accessibility. Only a single drill hole was collared during the entire existence of the dam and lake. In addition to drilling, indirect survey methods – geophysical measurements – were also used. These included geoelectrical, magnetometric, thermic and gravimetric methods as well as methods of seismic survey. In the dam lake itself, in the area adjacent to the dam, water resistivity and water temperatures were measured. In addition, sonar measurements were used to identify the shape of the bottom.

A great majority of geophysical work was carried out during the existence of the Soviet Union, mainly at the end of the 1970s. It is difficult to obtain the results of such measurements, particularly as far as the primary results are concerned, i.e. the field diaries and background materials providing the data on the location of geophysical measurements. The authors of this paper managed to obtained the outputs of some work, namely at the geological workplaces in Dushanbe and Tashkent. It is probable that all the data were also stored in some of the Moscow archives, but these are now unavailable to the authors of this paper. Despite all such problems, we were successful in obtaining an overview of the types of geophysical work that had been carried out at the site of interest. We want to share the results obtained in this period of work with all colleagues and show what knowledge has been gained using geophysical measurements, what can be acquired by possible reinterpretation and what other possibilities of geophysical work exist in the investigation of the site concerned, particularly with the use of new methods of measurements and their processing.

In the past, geophysical work was chiefly focused on the body of the dam that had formed by slope movement on the right slope of the River Murgab. The purpose of these studies was to identify the structure of the natural dam and to contribute to the knowledge of the seepage pathway that enables a discharge of about 45 m^3/s. The other group of work can also include measurements of resistivity and temperature of water just behind the dam. Also, geophysically, slope deformations were studied on the banks of Lake Sarez. The background information that we have managed to obtain shows that the following types of work were applied at the individual sites. The background information that we have managed to obtain shows that the following types of work were applied at the individual sites:

- The Usoy landslide (the body of the dam)
  - Gravimetric measurement
  - Magnetometric measurement
  - Vertical electrical sounding
  - Low-frequency sounding
  - The charged body
  - Seismic refraction
  - Non-longitudinal seismic refraction
  - Measurement of water resistivity on the lake
  - Measurement of water temperature in the lake
  - Monitoring (leveling, geodetic monitoring)
- The Right-Bank landslide ("Pravoberezhniy sesuv")
  - Seismic refraction
  - Non-longitudinal seismic refraction
  - Monitoring (extensometry, leveling, geodetic monitoring)
- The Left-Bank landslide ("Levoberezhniy sesuv")
  - Seismic refraction
  - Non-longitudinal seismic refraction
  - Geoelectrical measurements
  - Magnetometric measurements
  - Monitoring (leveling, geodetic monitoring)
- The Bazaytash landslide
  - Non-longitudinal seismic refraction
  - Monitoring (geodetic monitoring)
- The Batasayf landslide
  - Non-longitudinal seismic refraction
- The Severniy Kazankul landslide
  - Non-longitudinal seismic refraction

In addition, gravimetry was used at two sites on the left bank of the lake.

The layout of geophysical measurements on the Usoy dam is in Figure 1. We can see that the whole area of the landslide (dam) was covered with magnetometric measurement; in addition, the area of the dam crest also with gravimetric measurement. In the places in which the seepage of water was expected from the lake into the River Murgab, more magnetometric and gravimetric profiles were added and the measurement was supplemented with the methods of vertical electrical sounding, low-frequency sounding and the mise-a-la-masse method. In addition to these measurements, seismic profiles (one of which drawn through the entire dam) and one long profile using low-frequency electrical sounding were made on the dam.

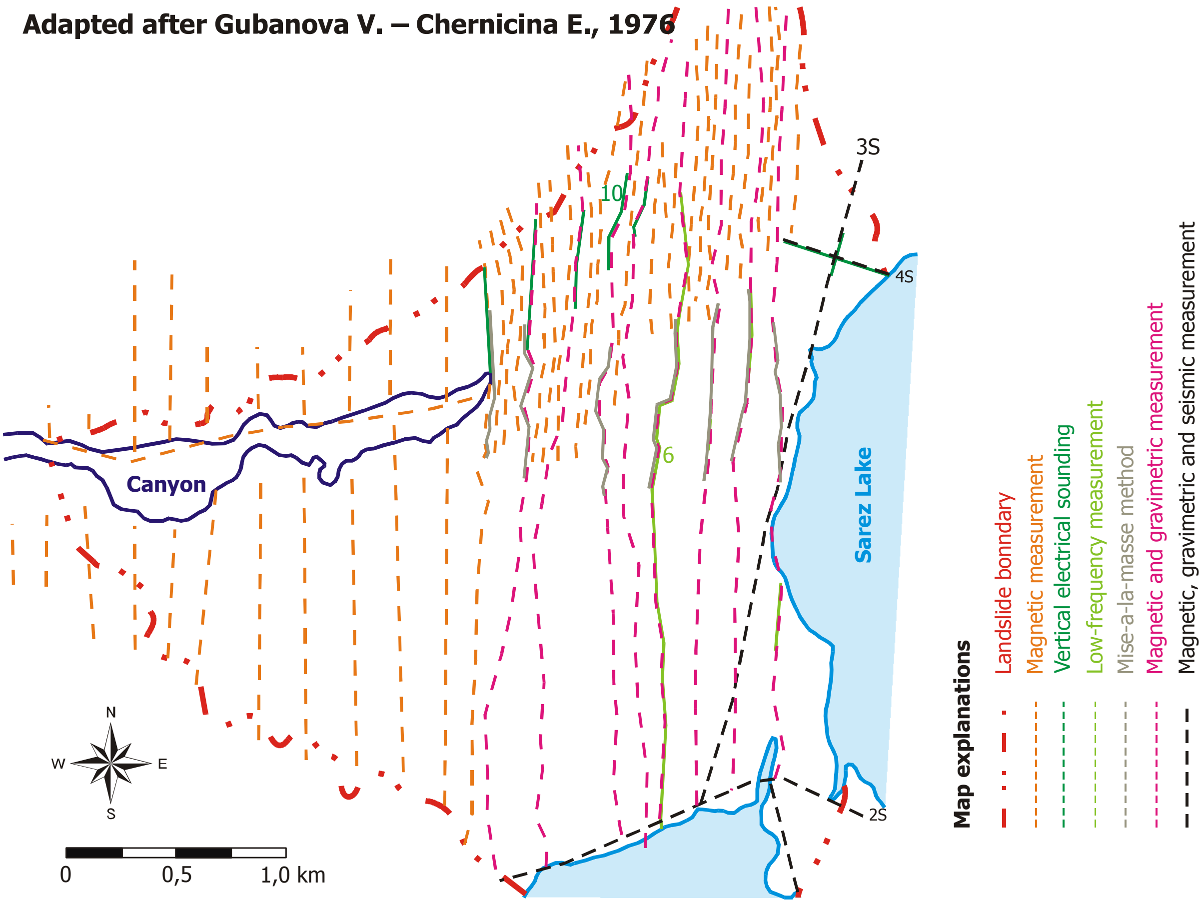

Fig. 1 Map of geophysical measurements (Adapted after Gubanova V. – Chernicina E. 1976)

An illustration of the results of vertical electrical sounding is given in Figure 2. The field measurement was obviously carried out with a smaller depth range, hence it was impossible to judge the thickness of the slipped material. However, we consider important the possibility to determine the places in which an increased flow of groundwater through the dam can be expected (the blue areas in Fig. 2). The clayey or fine sandy fraction was washed out by water flowing from the lake, or from a tectonic fracture in the left slope of the valley.

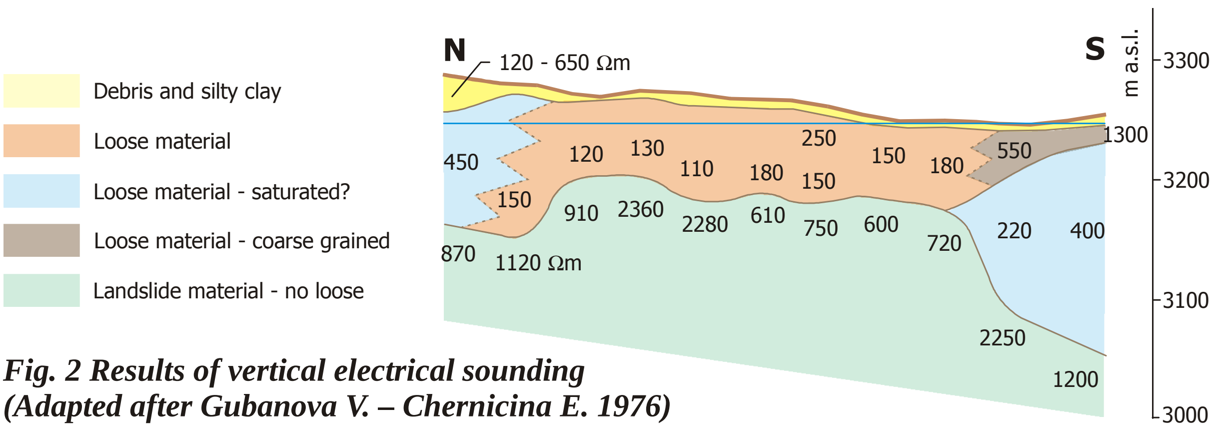

Fig. 2 Results of vertical electrical sounding
(Adapted after Gubanova V. – Chernicina E. 1976)

As a result, the resistivity values of this layer increased to 220 – 450 Ωm. It is therefore possible to express an assumption that the vertical electrical sounding would enable the preferred pathway of groundwater to be determined, both from the lake and also from the right side of the mountain range.

Figure 3 shows the results of measurement using low-frequency electrical sounding. The resistivity of the surface layer (thin violet line) was plotted to the graph from the measurement of low-frequency electrical sounding along profile P6. It changes from 10 to 380 Ωm. The filtered curve (thick red curve) does not show such a fluctuation anymore and it seems that it better describes changes in the rock mass. Similar curves can be obtained if the thickness of the first layer is observed. It ranges between 10 and 180 meters. As in the case of the resistivity, the filtered curve has a much smoother pattern in this case as well. Rapid changes of both the variables are indicative of a large variability of the dam. If mutual changes in the resistivity and thickness of the first layer are observed, it can be detected that in the places of increasing thickness its resistivity rises. It is possible that the places with lower resistivity were additionally choked and the resistivity of the originally slipped material corresponds with the resistivity in the places in which the thickness of the first layer is larger.

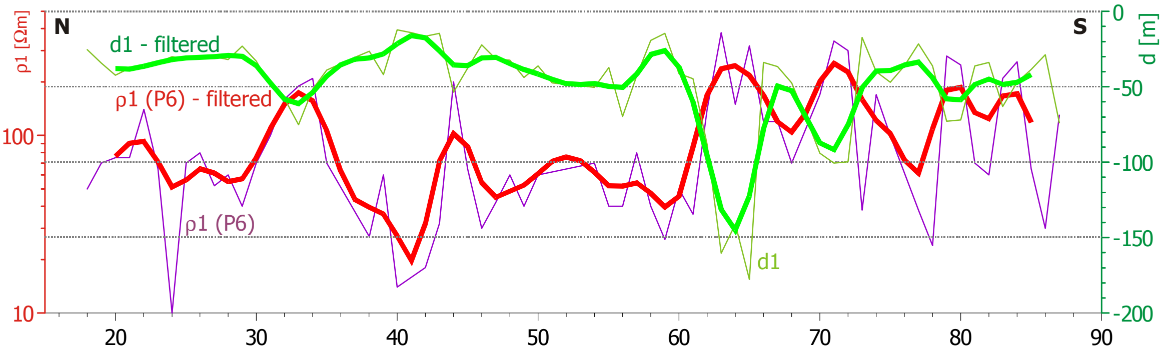

Fig. 3 Results of low-frequency sounding
(Adapted after Gubanova V. – Chernicina E. 1976)

The Bouguer anomalies detected by using gravimetric measurement are given in Figure 4. The anomalies along profiles P6 and 3S have a similar character (the fields decreasing towards the south). At the same time, however, the curves of both the profiles are shifted from one another roughly by three milligals. Whether this difference is due to the different procedures used in processing along the individual profiles, or whether it relates to the geological structure, it is not possible to decide from the background information obtained. However, the difference in gravitational acceleration in the northern third of the studied profiles is clear.

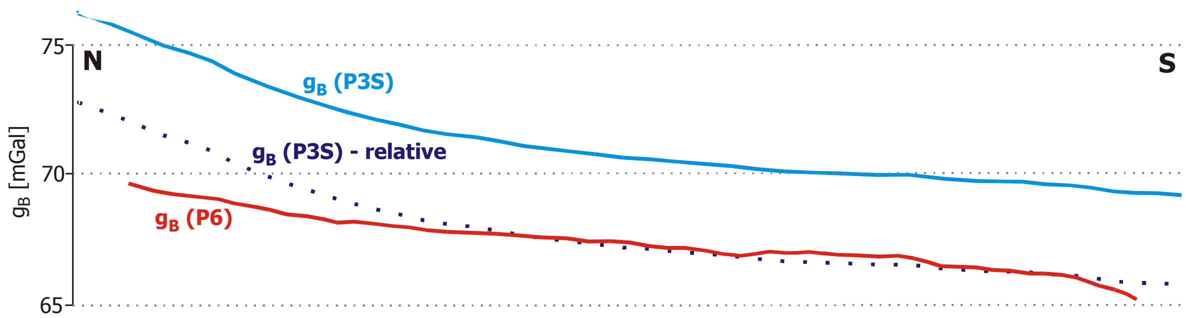

Fig. 4 Gravimetric measurements - Bouguer anomaly
(Adapted after Gubanova V. – Chernicina E. 1976)

Residual gravimetric anomalies of Δg were detected on gravimetric measurements, having magnitudes up to 3 milligals (mGal). The interpretation of these gravimetric measurements will be described below. The magnetometric measurements show that the detected anomalies are local and cannot be correlated over a greater distance. The anomaly of the vertical component of the Earth's magnetic field (Z), having a magnitude of about 300 nT and detected on profile P6, could not be correlated to other profiles (Fig. 5). The anomaly is thus obviously caused by a sporadic block of magnetic rocks, which was snatched and dragged down with other non-magnetic rocks during slope movement.

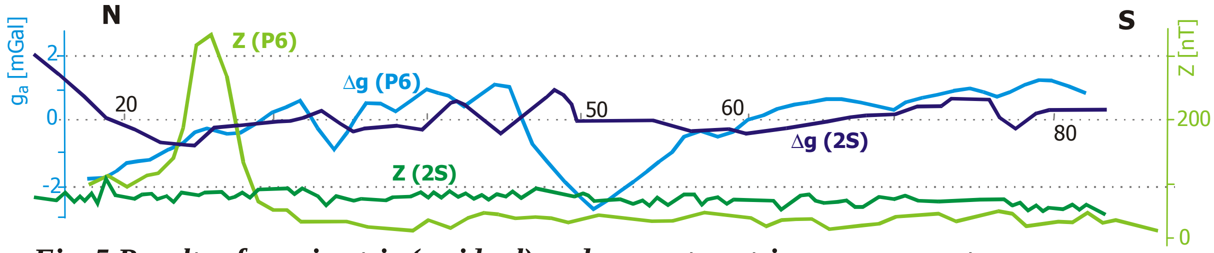

Fig. 5 Results of gravimetric (residual) and magnetometric measurements (Adapted after Gubanova V. – Chernicina E. 1976)

The gravimetric measurements interpreted as areal measurements in the area of the "crest" of the dam indicated good possibilities of gravimetry, even in these complicated conditions of measurement (Fig. 6). It was possible to identify two areas with a lack of materials (the green areas) and, in contrast, places with a relative surplus of materials (the orange areas).

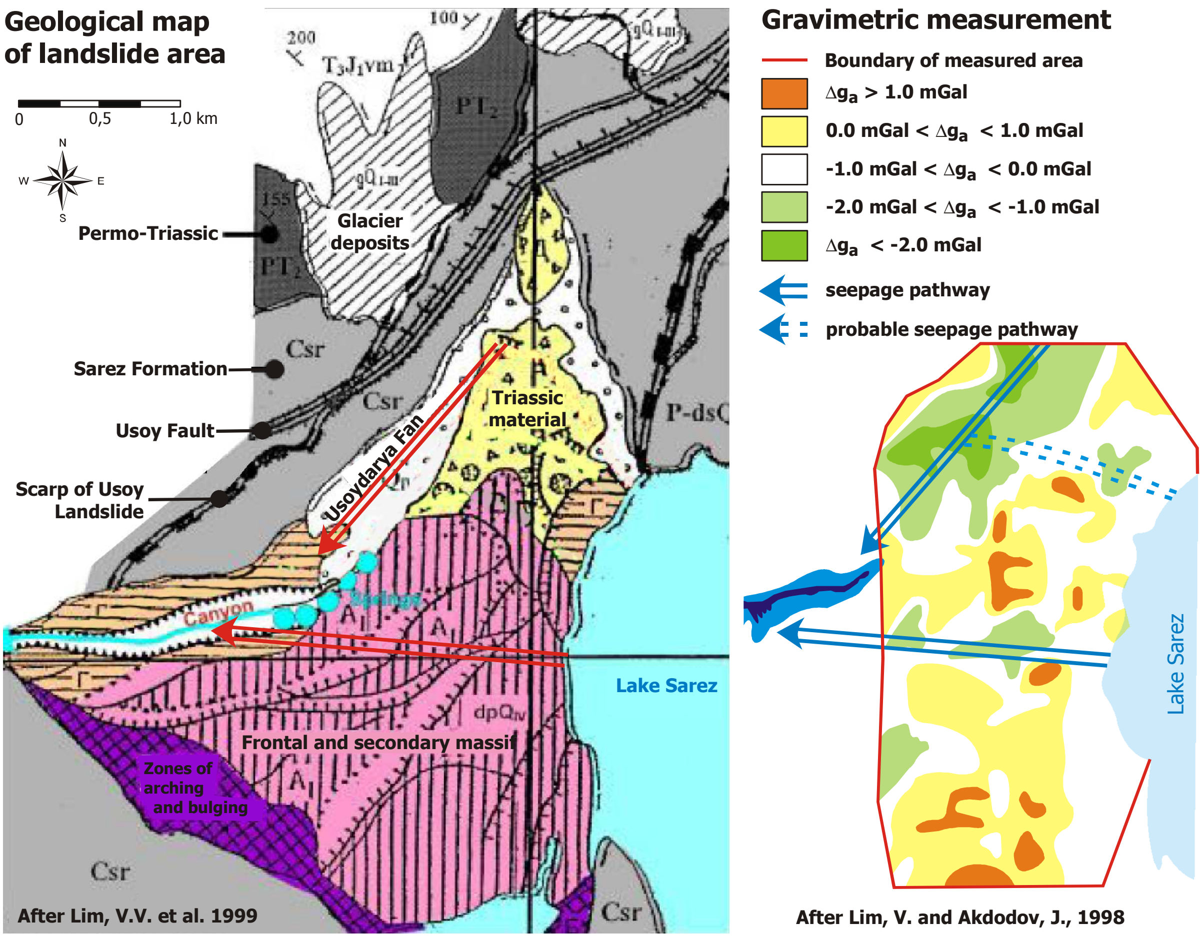

Fig 6. Geological map of Usoy dam and result of gravimetric measurement (adapted after Lim, V. and Akdodov, J., 1998 and Lim, V. 1999)

Particularly the places with a lack of materials are important for the understanding of the behavior of the dam and for the prediction of the behavior for the future. The more extensive gravimetric minimum in the northwestern part of the studied area corresponds to the place described as the “Usoydarya Fan”. It is possible that this fan (dejection cone) is responsible for the whole lack of materials, but it is rather probable that clayey and fine sandy fractions were washed out in this fan and its basement, and even today there is an intensive flow of groundwater in it, including water that can flow in from the Usoy Fault. This whole belt leads into the canyon. The second place with a lack of materials corresponds in all likelihood to those places in which water infiltrates from the lake through the dam body into the canyon. The regional gravimetric field shows reduced values upstream from the dam, but so far no attempt has been made to interpret these anomalies quantitatively. Modern computation methods would certainly made such a procedure possible.

Figure 7 shows the results of seismic measurements, both longitudinal and non-longitudinal. The results of measurements show that it was possible to determine the total thickness of the slipped materials, i.e. the height of the dam. Further detailed subhorizontal division of the dam body was not successful either by longitudinal or non-longitudinal measurements.

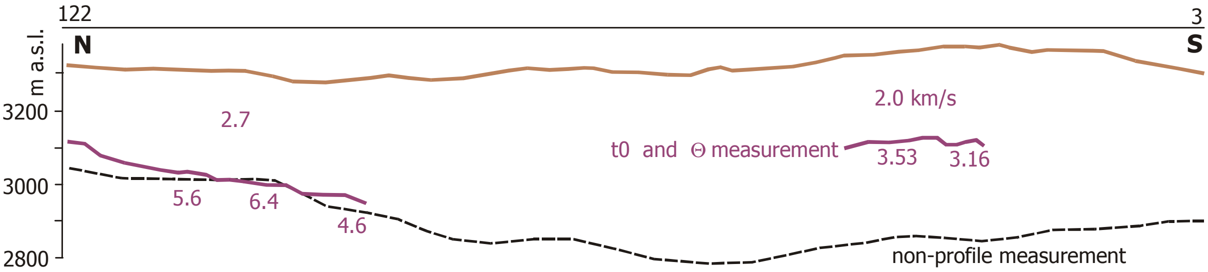

Fig. 7 Results of seismic measurements (Adapted after Gubanova V. – Chernicina E. 1976)

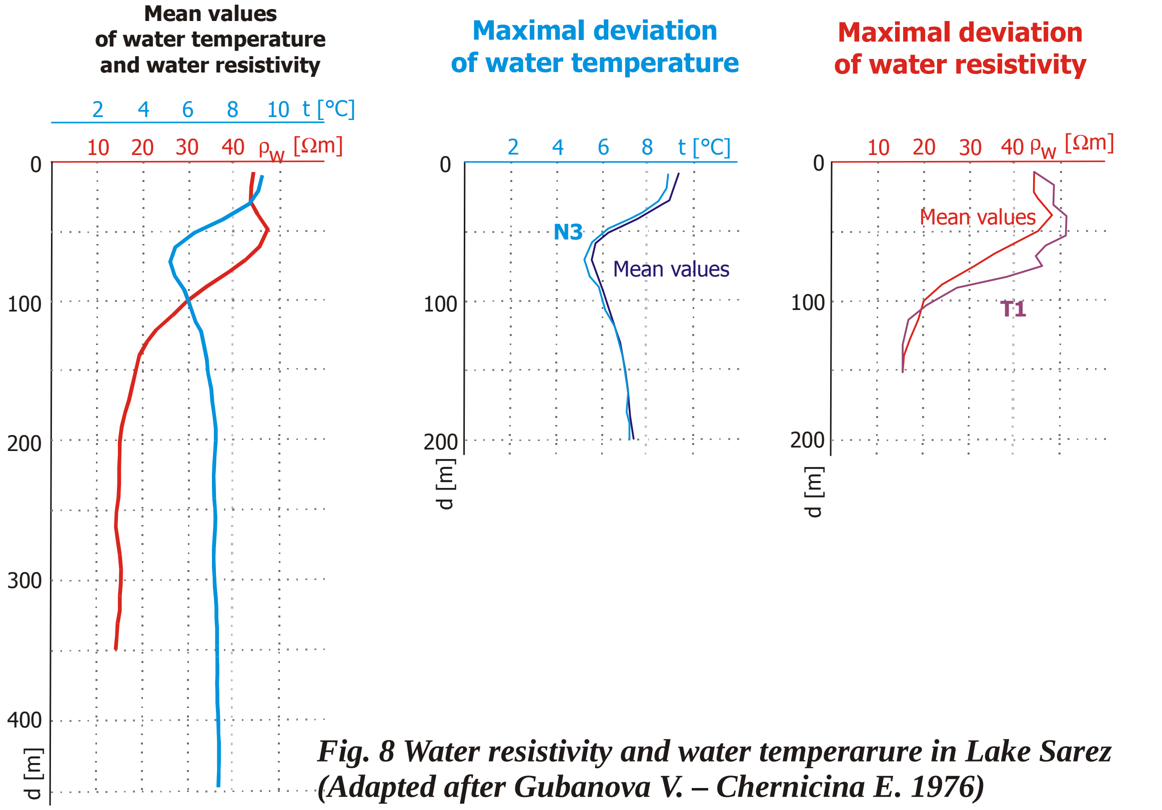

Fig. 8 Water resistivity and water temperarure in Lake Sarez (Adapted after Gubanova V. – Chernicina E. 1976)

The eighth figure shows the results of the measurement of resistivity and temperatures of water in Lake Sarez, in the part adjacent to the Usoy landslide. The results in all places of measurement are similar and the mean values of both the variables are depicted in the left partial graph. First, the resistivity of water moderately rises from the water surface down to a value of about 48 Ωm. Then, a relative rapid drop follows down to a depth of 130 meters where the value of resistivity reaches 20 Ωm; the subsequent drop continues down to the final depth of 350 meters where the lowest value of 14 Ωm was measured. The maximum deviations of resistivity up to 15 Ωm were detected in place T1. The mean temperature of water decreases from the water surface from a value of 9.2°C to 5.2°C at a depth of about 70 meters. Then, the temperature rises to 7.2°C at the final depth that was reached (about 450 m). The maximum deviation – 0.4°C – was detected in place N3. The results obtained clearly confirm that water in Lake Sarez changes from place to place and that greater deviations are in resistivity. To explain this in more detail, it would be necessary to make more measurements in a time series that would describe at least one year.

3. A Proposal of Other Geophysical Work

The results of the previous work and the development of instrumentation equipment and processing methods show that at the site it would be possible to come up to a new stage of geophysical measurements. New instrumentation equipment offers the application of new methods, and the implementation of the modern component base into the construction of instruments has significantly reduced the weight of apparatus used. Therefore, it would be possible to move in the terrain more easily with modern equipment, and thus to have the possibility of measuring even those areas which were practically inaccessible with old equipment.

Prior to starting new geophysical measurements, we recommend that all available materials about the already accomplished geophysical measurements be found. It is necessary to attempt to obtain these materials not only in Tajikistan, but also in Tashkent and, if possible, also in Moscow. It is necessary to reinterpret previous measurements using new methods of geophysical measurement processing and to evaluate all measurements comprehensively, not only each method separately.

As the second step we propose to process satellite images which cover the site. It would be most suitable to obtain images in a broad time span to monitor changes that took place over a given period at the site. For study we consider appropriate using classical images with low resolution, but particularly multispectral images and images with high resolution. It is known to the authors of this paper that there are available archive images from the ASTER satellite (in sixteen periods of time in a range of 2001 – 2008), from the SPOT satellite (with resolution up to 2.5 meters in a range from 2000 to 2008) and from the IKONOS and QUICKBIRD satellites.

The following methods are proposed as new geophysical measurements:

- Time-Domain Electromagnetic Exploration to detect subhorizontal boundaries down to a depth of 500 meters. This method can be applied both to the dam of the lake (the Usoy landslide), and also to all slope deformations in the area.
- Microgravimetric measurement with a microgal gravimeter to locate places of low density and thus also to determine predisposed seepage pathways. It would be appropriate to apply this method mainly to the northern part of the Usoy landslide for specifying two potential seepage pathways.

- Gravimetric profiling measurement on the dam and below the dam could provide a picture about the deeper geological structure and decide whether the minimum of gravitational acceleration so far identified depends on the lower bulk density of the displaced material, or whether it corresponds to the fracturing of rocks along the fault belt in the valley of the River Murgab.
- Measurement of spontaneous polarization using special electrodes to locate seepage pathways on the downstream side of the dam.
- The mise-a-la-masse method using special electrodes to locate seepage pathways.
- Seismic measurements in the form of seismic refraction and reflection, including the possibility of applying measurement using transverse waves.
- The application of seismic tomography would enable the geological structure to be explained in cross profiles of the dam.
- The application of modern 3D sonar devices for the accurate description of slopes below the groundwater table.
- The use of the method of laser interferometry would enable vertical deformations not only of the dam itself but also all of the other areas of interest to be observed.
- The use of laser scanners to monitor changes in the ground surface, particularly to observe changes in the canyon being formed by water seeping through the dam. Scanning of this site from the right and left slopes of the River Murgab would enable a perfect 3D model of the area of interest and a 3D visualization of the chronology of its development to be obtained.

4. Conclusion

The results obtained from the preliminary study of the previous geophysical measurements have confirmed the vision of the authors of the usefulness of the application of geophysical methods in the study of the area in the vicinity of Lake Sarez. The study of the archive materials (though incomplete) has shown that the measurements already made have indicated much of the structure of the Usoy landslide itself (the natural dam of Lake Sarez), but also of the other monitored areas. The processing of the results of the previous measurements by new interpretation techniques together with the application of new geophysical measurements in combination with the use of the methods of remote sensing would undoubtedly help supplement the knowledge of the structure of the dam, the position of the shear planes of the individual landslides and possibly also the geological structure of other important sites around the lake. Such knowledge would certainly enable the risks of individual natural processes to be specified more precisely and the critical states to be determined better, thus contributing to the reduction of the risk of the origination of unpredictable events. All these circumstances would increase the safety of the population not only in the basin of the River Murgab, but also in the basins of other rivers through which the water from Lake Sarez travels into the Aral Sea.

References:

1. *GUBANOVA, V. – CHERNICINA E.*, Rezultati inzhenerno geologicheskich issledovaniy v rayone Sarezkogo ozera i dolin rek Murghob i Nartang, *1975 – 1976, Dushanbe, UGSM TSSR, 1976.*
2. *HORSKY, O. – BLAHA, P.*, The Application of Engineering Geology to Dam Construction, *Repronis, Ostrava, 2011, 296 p.*, ISBN 978-80-7329-278-2.
3. Lake Sarez risk mitigation projekt, Stucky Consulting Engineers Ltd, Renens, 2003.
4. LIM, V.V. – AKDODOV, Y., Opolzni Sareza, Uzbekgidrogeologiya, Tashkent, 1998.

5. LIM, V.V. et al., Озеро Сарез и экологические проблемы Средней Азии, *1999.*
6. PAPIRIN L. P., *Rezultaty injenerno-geofizicheskikh issledovaniy v rayone Sarezskogo ozery I dolin rek Murgab i Bartang za 1975 – 1977. Chats 4. Geofizicheskoye issledovaniya. Tom 9. Tekst.,* Dushanbe, Gosudarstvenniy fond geologicheskoy informacii o nedrakh Respubliki Tajikistan Glavnogo upravleniya geologii, 1977.