Another well-documented example has been reported from the Kali Gandaki Valley in Nepal. There, about 55,000 years before the present (Pohl, 1997), a natural dam of similar size to the Usoi dam was formed from a huge landslide (Hanisch, 1995). The lake had a maximum depth of about 600 m and a length of as much as 35 km. It silted up totally; the remains of the lake sediments now exist as widespread horizontal terraces (Fort, 1976; Iwata et al., 1982).

3.3.2.3.2 Safety against internal sliding processes

The second type of failure of earthfill dams normally occurs as sliding within the body of the dam, i.e. between the two faces (Newmark, 1965: photo 5). The controlling factor in this case is the internal water pressure in the dam that decreases the effective stresses in the material. Internal erosion in a dam can cause the maximum water pressures within the mass to migrate downstream; if this process continues, the stability will gradually decrease, and finally sliding can occur within the dam. A large slide of this type could also affect the large-scale stability of the dam because the mass of the dam would decrease.

For this reason, a preliminary calculation of the internal slope stability of the upstream face of the Usoi dam has been performed using Gussman's method of "Kinematic Elements" (Gussmann, 1982). Differing from classic methods, this technique is able to consider the movements between blocks defined arbitrarily by the analysis of the kinematics of landslide movement (fig. 13). The couples of friction/cohesion can be defined separately for each interface between elements or at the bases of the elements.

In the present analysis (fig. 13), the following parameters have been applied:

Specific weight of the dam material:
$\gamma = 22$ KN/m^3

Property values for interfaces near the bottom of the dam:

Angle of internal friction:	$\varphi = 25°$
Cohesion:	$c = 10$ KN/m^2

Property values for interfaces between individual elements:

Angle of internal friction:	$\varphi = 40°$
Cohesion:	$c = 0$ KN/m^2

The influence of a heavy earthquake has been estimated using the pseudostatic approach, adding to the vertical acceleration, g, a horizontal component of as much as 0.5 g, which is an extreme value. (In future studies the more accurate dynamic approach by Newmark (1965) and Jibson (1993) should be applied.)
Note that the curve of potential failure has to be considered as a first estimate until better understanding of the internal structure of the dam becomes available.

The following safety factors have been obtained from these analyses:

FS = 2.48 (water table at elevation 3263 m; no horizontal acceleration)
FS = 1.15 (water table at elevation 3263 m; horizontal acceleration = 0.5 g)
FS = 2.53 (water table at elevation 2800 m; no horizontal acceleration)
FS = 1.43 (water table at elevation 2800 m; horizontal acceleration = 0.5 g)

This signifies that, even under the worst circumstances, the stability of the dam against slope failure towards the lake is fairly high, based on the knowledge that a horizontal acceleration of 0.5 g is an extreme value to assume in a pseudostatic earthquake analysis (Newmark 1965).

The local slope stability of the downstream face cannot be estimated in this report because the internal structure of the dam is not known. As described in the next section, all of the observed leakages of water from the dam emanate at roughly the same level, approximately 140 m below the lake level (about 350 m above the base

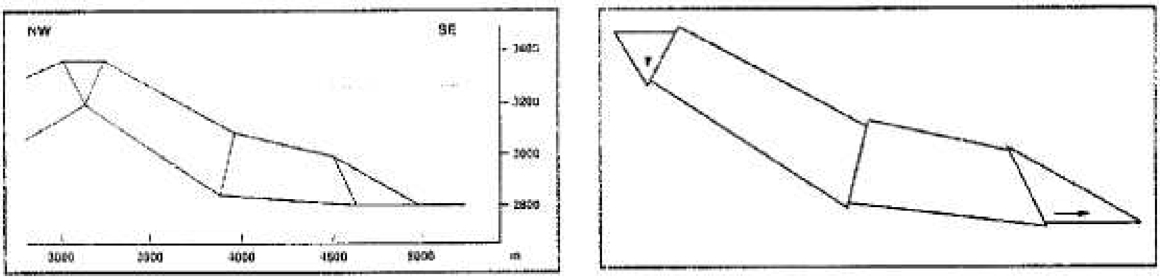

Fig. 13. Kinematics of a potential slide failure of the upstream side of the Usoi landslide dam using the "Method of Kinematic Elements" of Gussmann (1982, 1992). The angle of internal friction between the elements is assumed to be 40° and the cohesion to be zero. It is further assumed that the angle of internal friction between the base of the dam and the underlying geologic material is 25° and the cohesion along this contact is 10 KN/m². For further explanation, see the text.

of the dam). This indicates that (at least for the downstream part of the dam) the lower two thirds of the dam have a very low permeability. The horizontal extension of this material is not known at present; therefore, the water table, the degree of saturation, and the internal water pressure of the dam cannot be estimated. Our present understanding of the water-pressure distribution and drag effects of the flowing water is inadequate to draw final conclusions on the internal stability. This configuration, however, is critical for the stability because the presence of such a zone controls the water-pressure distribution in the dam; this should be the subject of future studies.

At the downstream slope, along the line of seepage springs, a small canyon has formed, with a depth of approximately 20 m (photos 14 and 15). This canyon has developed partly in the dam material at its toe but mainly in a flood plain of debris-flow deposits that are resting on the downstream slope of the dam. The amount of erosion of the dam foot is absolutely minor, so that worries about the influence of dam stability are not justified (cf. State Committee on Emergencies, 1997).

Photo 14. Seepage springs on the downstream side of the dam causing erosion of the debris-flow (i.e. flood-plain) deposits lying on the blocky dam material to the right (bottom of photo). Photo credit: Jörg Hanisch.

3.3.2.4 Seepage

Lake Sarez drains only by seepage flow through the dam. At the top of the dam no indications of a former natural spillway channel (i.e. a surface outlet) have been detected and the dam has never been overtopped. The annual fluctuations of lake level are reported to be ± 6 m.

Seepage measurements began on a regular basis in 1943; since then, the discharge has overaged a constant value of 45 m^3/s (State Committee on Emergencies, 1997) The annual variation has been 35-80 m^3/s, with 28 m^3/s and 84 m^3/s as the extremes The area in the vicinity of the springs on the downstream slope shows no signs of ongoing erosion, and from a visual inspection no sediment transport can be detected. No firm conclusion can be drawn as to possible sediment erosion and transport by piping from this brief inspection. However, because the discharge through the dam has remained constant during the period from 1943 until today, the rate of internal erosion must be very low and not apt to create a major problem. It is important, however, to continue monitoring the seepage.

One important feature of the leakage is that the springs are all located on more or less the same topographic level, which is approximately 140 m below lake level (photo 15). This indicates that the lower part of the dam, with a height of about 350m, has a very low permeability. On the contrary, the upper part of the dam is very permeable. The blocky dam material visible in large parts of the dam surface should be responsible for this high permeability.

The reported extremely high flow velocities through the dam of as much as 5 m/s (State Committee on Emergencies, 1997) are questionable Such tremendous and highly turbulent flow conditions would require large open, and continuous, channels through the interior of the dam. Because the seepage springs emanate quietly and the water-table difference is 140 m between inflow and outflow, build-up of considerable water pressures somewhere in the interior of the dam should be a consequence (with the effect of substantial erosion at the seepage springs). Therefore, the given hydrologic data should be carefully examined and additional testing using markers should be conducted.

Last, but not least, it should be noted that the dam with its controlled normal seepage minimum of 35 m^3/s, plays an important role in the seasonal water regime downstream from the dam. The lake-level fluctuations reflect the function of the dam as a buffer to downstream flow. The lake is thus supplying a rather constant discharge during the long dry season.

Photo 15. Line of seepage springs along one topograpic level forming the post-dam Murgado River. Photo credit. Jorg Hanisch

3.3.2.5
Potential damage from overtopping by surge waves

One very important question is the possibility for the dam to withstand an overtopping wave without severe damage A study of the granulometric composition of the dam has been conducted (State Committee on Emergencies, 1997) with the purpose of estimating the vulnerability against erosion due to overtopping. The results from this study could be very useful in a sensitivity analysis. The other part of the problem is to estimate the features of a landslide-generated displacement wave when it reaches the dam. Several attempts have been carried out to model such a wave; however, the results have been controversial (State Committee on Emergencies, 1997). The studies have provided estimates of waves up to 180 m high following a mega landslide of 2 km^3 rushing into the lake near the dam (State Committee on Emergencies, 1997,1999). It is beyond the scope of this reconnaissance report to judge these scenarios. However, the probability of occurrence of landslides this large will be discussed in section 3 3.2.7.2. Despite the difficulties in defining the vulnerability of the dam to an overtopping wave, some general comments from the observations during the mission can be made:

- The northern part of the dam (at least at its surface) consists of blocks of various, but large, sizes with large open voids between them. This composition is advantageous to the dissipation of the energy of an overtopping wave (the blocky material would be ideal for the construction of breakwaters or large-scale riprap), thus offering high resistance to erosion;
- The central part of the dam (at the surface) does not have very large blocks, and the voids are mainly filled with fines. However, this negative aspect of the surface structure is counterbalanced by the considerably greater height of this part of the dam;
- The southern part of the dam is by far the highest, having a freeboard of up to 270 m. Additionally, the dam material consists mainly of the same extremely blocky material as in the northern part of the dam. Thus, this part of the dam is considered to be, by far, the most stable part
- The mechanism of dam failure by overtopping surge waves has to be well understood before judging the possibility of such an event.

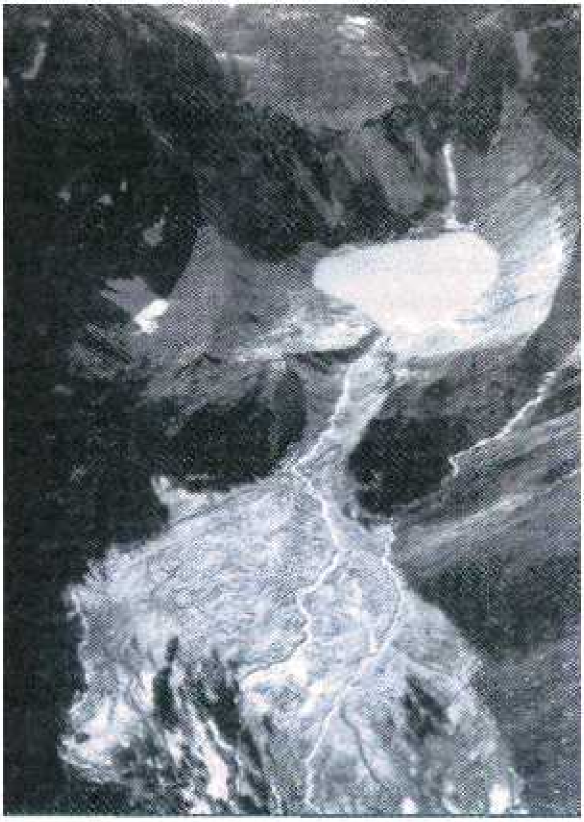

Photo 16. Typical outburst of a moraine-dammed glacier lake: A displacement wave generated by a huge ice fall overtopped the terminal moraine, surged down the steep outer face, and began eroding a narrow breach into the dam by retrogressive erosion. The lake emptied in several hours, resulting in a devastating debris flow (From Evans and Clague, 1994).

The State Committee on Emergencies (1997) refers to outbursts of moraine-dammed glacier lakes. However, the mode of failure of moraine-dammed lakes may be quite different from overtopping failure of landslide-dammed lakes. In most cases of overtopping of a moraine-dammed lake, the surge wave rushes down the steep outer face of the moraine and starts eroding the dam at its toe (photo 16). By retrogressive erosion, a narrow and steep breach is formed which, when reaching the lake itself, leads to emptying in only a few hours (Lliboutry et al., 1977; Evans and Clague, 1994; Hanisch et al., 1998). Because of the comparably flat outer face of the Usoi dam, this mechanism of failure is extremely unlikely in the present case.

3.3.2.6 General observations

Most of the rock mass around Lake Sarez is heavily fractured from older and ongoing compressive tectonic activity This has led to deep weathering, and the formation of thick colluvial soil layers on the slopes. The consequence is - as a result of the generally steep slopes of the region - development of many kinds of permanent downslope mass movements (cf. Watanabe's chapter 5).

A new situation was created with the formation of the lake and the rise of the water level to parts of the slopes that historically have been almost dry. The lake water has infiltrated the soils and the underlying fractured rock, leading to reduced friction angles, buoyancy effects, and potentially to pore and joint water-pressure development during lake-level fluctuations. These effects are apt to destabilize the slopes Another negative influence comes from wave action along the shore lines, which leads to undercutting of the slopes.

3.3.2.7 Unstable slope at the right bank opposite the base camp

3.3.2.7.1 Background

From the very beginning of the Lake Sarez investigations, the "right bank" slope has attracted the concern of researchers. The unstable slope in question lies about 5 km east of the dam and has a width at its foot of about 1 km (photo17). Numerous open cracks are present in the slope; these have been monitored for many years by Russian observers. Movements of up to 10 cm/year have been noted (State Committee on Emergencies, 1997).

Since August 1998, a set of modern, robust extensometers has been installed. One of these is a wire extensometer; the other six are rod extensometers, each equipped with two protractors that are able to register slope movements in three dimensions. The accuracy of these extensometers is about 0.5 cm and 1°.

Photo 17. Unstable slope above the right bank of Lake Sarez opposite the base camp. Lower right part of photo: scarp of active rock fall, consisting of a face of solid rock covered with about 60 m of colluvial soil. Lower middle part, dashed line: landslide that moved downslope about 100 m in 1911, but for some reason stopped at its present location. Visible part immediately above water level: landslide material, volume ~ 150,000 m^3. Lower left part, stippled line: probably an older landslide of the same type as in the middle, but much more deteriorated and eroded. Upper right part: smooth slope surface with thick colluvial cover intersected by numerous cracks as much as 3 m wide (arrow), most of which are monitored by extensometers. Hatch-stippled line: approximate extension of maximum possible landslide as estimated by Tajik workers (State Committee on Emergencies, 1997). Photo credit: Jörg Hanisch

Many more cracks are being monitored by sets of two bolts with conical tops that are fixed on each side of open cracks. The accuracy of these installations is not greater than 1 cm. Some of these installations are not well positioned because they measure movement approximately perpendicular to the direction of slope movement.

Two of the rod extensometers have registered movement: one indicated movement of 1 cm in 9 months, and the other showed 2 cm for the same period. However, the nearby wire extensometer, did not register any movement (according to reports, it was out of order for some time).

3.3.2.7.2 Former landslide scenarios on the right bank

The hypothesis that a substantial part of the right bank could slide into the lake - such as happened in 1963 at Vajont, Italy (Mueller-Salzburg 1987) - and could generate a disastrous displacement wave able to overtop the Usoi dam has led to a series of disaster scenarios (State Committee on Emergencies, 1997, 1999). The volumes of landslide masses involved in these disaster scenarios range from 0.35 km^3 through 2.0 km^3. The heights of possible waves were calculated by a "mathematical" and a "physical" model. These heights ranged from 55 m to 180 m, and volumes of water overtopping the dam ranged from 16 million m^3 to 225 million m^3. These calculations showed that a landslide volume of up to 350,000 m^3 would not cause an overtopping wave, and thus would not harm the dam.

The original files of these calculations were not accessible to the authors. Thus, it is not known on what basis estimates regarding the depth and shape of sliding surface (surface of rupture), water depth, underwater morphology, and velocities of sliding were used in these computations. However, the values of these parameters are crucial to the entire hazard assessment and should be re-assessed by specialists.

3.3.2.7.3 New findings

Our one-day climb up the unstable slope revealed several observations that provide a different view of the stability of the right bank slope:

- At an elevation of about 3400 m, a series of cracks, at least 100 m long, are present. These cracks show no extensional behaviour, but clearly indicate compression. This means that, at least at this place, the cause of the landslide movement does not come from the foot of the slope (e.g., undercutting by wave action, water infiltration), but the stress comes from higher parts of the slope above the cracks;

- Most of the observed open cracks parallel to the contour lines of the slope show only minor vertical displacement, i.e., the movements have gone parallel to the gradient of the slope. This points to a rather shallow sliding surface (surface of rupture);

- In the middle part of the slope (marked by M in photo 17), there are clear indications of a long-lasting, but slow, sliding process of the thick colluvial cover. The landslide area lies about 20 m deeper than the immediate upslope area and is separated by a pronounced lateral escarpment. According to Tajik colleagues, the seismic-reflection studies carried out during former Russian investigations revealed a thickness of the colluvial debris of up to 60 m;

- The driving force for these slope movements seems to be loading by the permanent rock-fall activity from the cliffs at the top of the slope at nearly 5,000 m elevation;

- To the west of the slope, at about 4,000 m elevation, an approximately 500-m-long slope-parallel crack has been mapped. Another open crack is present as a westward continuation of this large crack, but within a rock cliff. The slope below this crack down to the shoreline seems to be free of open cracks. This could be an indication that this long and straight crack is caused by a process called "mountain splitting"or Sackung. This is a stress-release effect along valley walls, especially those that have previously been occupied by glaciers. Typically, this mountain splitting results in no well-defined, deep surfaces of rupture; instead, the differential movements are compensated by very slow creep movements. This interpretation should be scrutinized during forthcoming investigations;

- The one drill hole by Russian scientists at the foot of the unstable slope provided "evidence" for a deep-seated surface of rupture at a depth of about 175 m. The (simplified) records of this bore hole reveal "sand" at this depth with rock above and below. According to engineering-geologic drilling practice, this is likely a misinterpretation of drilling results. The "sand" could be the result of core destruction during drilling.

To summarize: there is a series of uncertainties in the description of the indications of slope movements on the right bank. From the impressions gathered during our one-day field visit, slope instabilities on the right bank can be subdivided into three different types of movements:

- Rock falls/slides along the steep shore line (fast movements);

- Debris slides and debris flows along the entire slope (relatively slow movements);

- Mountain splitting (cracks due to stress release along the valley flanks; extremely slow movements).

These slope movements on the right bank should be carefully examined, applying modern engineering-geological methods and experience. At the moment, it seems to be extremely unlikely that there is a deep-seated surface of rupture able to create a disastrous landslide with a volume of even 1-2 km^3. Compared, for example, to the well-investigated 1963 Vajont disaster in Italy (e.g., Mueller-Salzburg, 1987), in which a well-defined pre-existing bedding plane served as a deep-seated surface of rupture, we have found no evidence that the right-bank slope above Lake Sarez has such a potential surface of sliding. The open cracks on the slope seem to have quite different origins from those at Vajont. However, these cracks and the depths of the surfaces of rupture should be investigated in much greater detail.

3.4 Summary and conclusions

The most important features of this study were:

- The general stability of the dam and especially its vulnerability to overtopping leading to erosion;

- The right part of the dam with a minimum freeboard against overtopping;

- The seepage through the dam, which has formed a canyon on its downstream side;

- The right slope above Lake Sarez, approximately 5 km upstream from the dam where instability has been verified.

The macro-scale stability of the dam is considered to be high because the enormous mass of mainly rock debris forms a huge plug in the valley. No signs of former overtopping have been observed. No evidence of piping caused by the seepage through the dam could be detected. Erosion at the seepage outlets is strictly restricted to the young and loose sediments from river and debris-flow action of a tributary stream that reaches the downstream side of the dam from the north.

The slope instabilities on the right slope above the lake (i.e., on the right bank opposite from the base camp) have been divided into three types of movements:

- *Rock fall/slides along the shore line (fast movement);*

- *Debris slides and debris flows along the entire slope (relatively slow movement);*

- *Mountain splitting (cracks due to stress release along the valley flanks); extremely slow movement; probably stable at present.*

From the discussions held and the observations made during the six days spent in the field, the following conclusions can be drawn:

- The most important conclusion of the field visit is that there is no danger of a general dam failure from the pressure of the lake against the upstream face. Even under the worst imaginable circumstances of an extremely heavy earthquake with horizontal accelerations of 0.5 g, the estimate of the safety factor still results in a safe value;

- Both the dam area and the "right bank" problem need a modern strategy of hazard prevention and hazard mitigation. An attempt is made in figure 18 to show the synergetic correlations of the two approaches. For a short-term strategy, both approaches should be pursued independently. In the long term, however, the mitigation approach, including its major component of a well-elaborated early warning system can never work satisfactorily. If, for example, a serious dam failure should happen after 30 or 40 years, the chance that the warning system would still be in function is very low. Additionally, the people living in the hazardous area wouldn't react properly because there certainly would have been several false alarms before.

This signifies that the disaster-prevention works should be finished within a reasonable time span. During this time – and especially during the practical implementation of any kind of prevention measures – the mitigation approach with its combination of monitoring, early warning, and training of the local people for preparedness is a prerequisite. Once the prevention work has been implemented, long-term monitoring of the entire Lake Sarez system has to be conducted on the basis of spot checking to ensure that nothing unforeseen will occur. In case of any unforeseen development, the strategy of hazard prevention/mitigation must be re-established;

- The partially confusing conglomeration of opinions, fears, controversial results of former experiments, and in most cases inaccessible original data of former investigations need urgently to be reviewed thoroughly. A geo-scientist – preferably an engineering geologist or a geotechnical engineer – able to read the Russian originals should have at least three full months for the study of sources;

- For the judgement of hazards along the shore lines of the lake and the corresponding risk assessment, an experienced engineering geologist with a good understanding of modern field techniques and analytical methods will be needed to work with local experts for at least two months in the field.

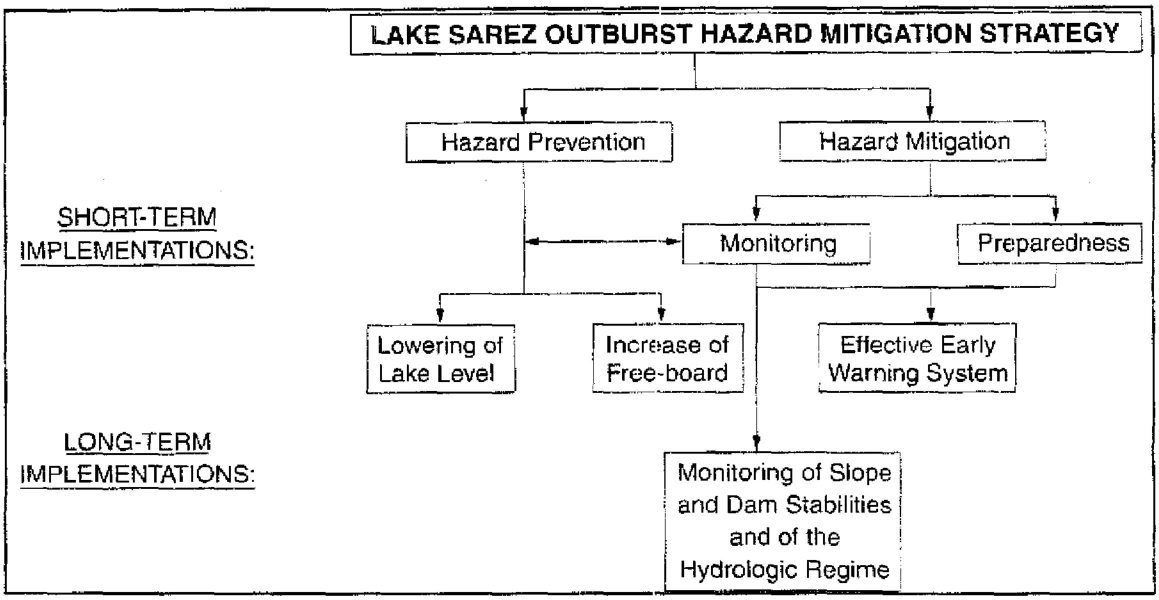

Fig. 18. Scheme of the proposed mitigation strategy: parallel work of disaster prevention and mitigation with interaction from the monitoring for a certain period and – once the hazard of overtopping of the dam by huge displacement waves will have been cleared (either by lowering the lake level or by increasing the freeboard) - the sophisticated early warning system can be abandoned and the monitoring of the dam and of the unstable slopes can be reduced to "spot" checks.

3.5 Recommendations

Based on the above conclusions, the following recommendations are made:

3.5.1 Usoi dam

- A search for and a review of publications that relate to the dam and the lake should be performed. Much of this material is expected to exist in Moscow and will be in the Russian language. Of particular interest are results from measurements that have been made over a longer period of time, such as the leakage through the dam and movements in the right bank. In general, the information on the dam before the establishment of Tajikistan as a sovereign State does not seem to be complete, and, for a hazard assessment to be conducted, it is essential to have access also to older information. A risk assessment is generally greatly improved if data exist over a long period of time.
- Seepage through the dam should be measured on a regular basis; this measurement should include determination of the presence of suspended sediments and an inspection of the downstream slope to detect possible new springs and changes in the existing ones.
- A hydrologic station should be installed near the foot of the dam to exclude influences from tributary rivers between the dam and Barchidev where the present station is located.
- The lower part of the dam, with apparent low permeability, should be further investigated. This seems to be possible only by using geophysical methods because drilling through the blocky material will be almost impossible. It is understood that this is not an easy task because, for example, seismic refraction data can be difficult to interpret for the very blocky parts of the dam.
- A manual for the dam should be set up and maintained. This manual should contain the basic information regarding the geology of the dam, data from earlier and ongoing measurements, inspection protocols, alarm levels for critical parameters, intervals and checklists for inspections, dam-safety organization, responsible persons, etc. The manual should be updated continuously when new information and data are available. Based on this, the hazard assessment can be improved and necessary measures can be planned. A crucial part is the organization and the distribution of responsibilities within this group.
- Earlier calculations of generated waves from a landslide into the lake should be reviewed and possibly repeated using advanced methods. Possible effects on the dam by the waves should also be included in the analysis.
- A feasible way of heightening the crest of Usoi Dam at its lower northern part should be considered The concept of doing this by well-calculated controlled blasting of one of the two steep flanks of the wedge-like escarpment immediately north of the dam should be considered. Special experience in this method of building dams was developed in the former Soviet Union (e.g., at the Medeo debris-retention dam north of Almaty, Kazakhstan, and at Nurek Dam, Tajikistan, the world's highest man-made dam).

3.5.2 Slope above the right bank

- The monitoring stations along the cracks on the slope should be improved. All simple distance-measuring stations should be replaced by 3D gauges or should at least be altered to triangular layouts. Some five additional wire extensometers should be incorporated into the monitoring scheme, with a 50-100-m array across the entire set of open cracks at any specific location.

- To determine the depth(s) of the surface(s) of rupture in the middle part (cf. photo 17) of the slope, two to three drill holes are required, followed by installation of inclinometers.
- Based on existing data and new findings, a totally new assessment of slope movements should be performed applying modern geotechnical methods and experience. The slope movements have to be divided into different classes of landslide activity (e.g., rock slides, rock falls, rock avalanches, debris slides, and Sackungen).
- For the interface to the new early warning system, the thresholds of slope movements, and especially the critical acceleration and velocity values, have to be defined properly.
- For the worst-case scenario, dealing with potential landslides with volumes of up to 1 or 2 km^3, the calculation of the potential height of overtopping and the displacement wave should be recalculated. It should be kept in mind that such an event could create a huge new landslide dam about 5 km upstream from the existing one. For this case, the water volume available to flood the Murgab and Bartang valleys after a potential breaching of the Usoi dam would be reduced considerably.

3.5.3 General recommendations

- For long-term monitoring of the dam and the slopes, it should be determined whether the so-called SAR (Synthetic Aperture Radar) system might be a useful tool. In this system, a radar satellite, which flies over the area every 2 weeks, is able to compare the images of successive flights. If some part of the morphology has changed between flights (horizontal accuracy approaching 0.2 m), the area in question is automatically printed in red. In this way, ground movements could be obtained automatically for an early warning system.
- A new set of stereographic aerial photos of the entire Lake Sarez area is required for the slope stability studies. Prior to this photography, benchmarks (with targets large enough to be registered on the photos) should be installed at crucial points.
- A seismic station should be installed near the Usoi landslide dam to obtain primary data on earthquake activity.

3.5.4 General remarks

Some additional remarks are made here that cover issues beyond the direct tasks of the geotechnical experts:

- It seems irresponsible to keep the base camp at its present location opposite the potential huge landslide (outlined so dramatically in the existing reports of the State Committee on Emergencies 1997,1999). A rock fall with a volume of only several tens of thousands of cubic metres could create a displacement wave able to wash away the camp installations. Preferably it should be removed to the top of the terrace behind the camp where the former Russian camp was situated;
- Any future calculation on the possible propagation of a potential outburst flood should keep in mind that such a flood would soon convert into a debris flow because of the abundantly available loose material comprising the dam and along the Murgab and Bartang valleys. The devastating forces and the reach of such a flow would be considerably greater than that of a high-water flood. Since no practical computer model for such a calculation is yet available (theory in Iverson, 1997), the model developed by Haeh (1996) seems to be the most appropriate because it includes the erosional effects of a flood. The most-used DAMBRK model by Fread (1984) should be used only as a first approach because it does not consider the very high densities (up to 2.4 ton/m^3) observed in debris flows.