Chapter 3

Geotechnical assessment of the Usoi landslide dam and the right bank of Lake Sarez

3.1 Introduction

Lake Sarez in the Pamir Mountains of Tajikistan was created in 1911 when an enormous landslide (volume: approximately 2 km^3) blocked the Murgab River valley. The landslide was triggered by one of the strong earthquakes typical of this region of active tectonism. The natural dam, which was named Usoi after a village buried by the landslide, impounded Lake Sarez. This lake has a surface elevation of 3265 m, is 60 km long, and has a volume of approximately 17 km^3, roughly one half the volume of Lake Geneva. With a height of about 600 m, the Usoi landslide dam is the highest dam, natural or man-made, in the world. Because it is not an engineered structure and because of the large volume of water it impounds, significant concern has to be given to the stability of this natural dam and to the slopes along the shore of the lake.

The studies of Lake Sarez and the Usoi landslide dam discussed here were conducted during a one-week field visit to the dam and the western part of the lake accompanied by two local experts, Dr. Anatoly Ischuk (Deputy Director, Tajik Institute of Earthquake Engineering and Seismology, Dushanbe) and Col. Yusuf Akdodov (Sarez Directorate, Tajik Committee on Emergencies, Dushanbe). Existing data were compared with visual observations in the field.

3.1.1 Terms of reference and targets of the hazard assessment mission

The "Disaster Hazard Assessment" sub-team had the task of assessing at a reconnaissance level the likelihood of a collapse of the Usoi landslide dam and the general vulnerability of the Usoi dam at a reconnaissance level. The team consulted with Tajik seismologists and Usoi dam experts in Dushanbe before departing for the lake, and during their field visits.

The duties of the team experts were the following:

- *Assessment of the overall stability of the Usoi dam,*
- *Assessment of the current state of water filtration through the dam and the threat that it poses due to possible internal erosion or "piping";*
- *Assessment of the threat posed by the right-bank landslide-prone slope above the lake;*
- *In consultation with Tajik seismological experts, assessment of the seismicity of the region and the probable impact of future earthquakes on the dam and the lake.*

The following scenarios had to be considered by the experts when performing their risk assessment studies:

- *Failure of the dam due to seismic shaking;*
- *Collapse of the dam due to internal erosion;*
- *Breaching of the dam due to overtopping following possible collapse of the right-bank*

slope into the lake or due to the formation of seiches (waves due to seismic shaking);

- *Instability of the dam due to the excessive pressure of the water in the lake on the dam structure;*
- *Instability of the upstream and downstream slopes of the dam;*
- *Progressive loss of stability of the dam and other areas due to renewed landslides or debris flows in proximity to the lake.*

3.1.2 Former studies

Extended investigations were carried out on the Lake Sarez problem by Russian and Tajik scientists and engineers from 1915 through 1992. Upon the independence of Tajikistan in 1992, all installations and investigations were abandoned. In August 1998, the Tajik State Committee for Emergencies began to install new monitoring systems.

The original Russian reports and publications are generally inaccessible. One English-language paper was found in the Proceedings of the 1984 International Symposium on Landslides in Toronto (Gasiev, 1984). Therefore, the reports and opinions obtained at the beginning of the mission are not always fully verifiable (State Committee on Emergencies, 1997, 1999).

3.1.3 Geological framework

The Pamir is part of the Himalaya - Hindukush - Karakoram - Pamir mountain belt, which is one of the tectonically most active in the world. It is dominated by a series of active thrust faults and associated wrench faults (State Committee on Emergencies, 1997, 1999). The Lake Sarez area lies within one of these major thrust faults (fig. 1). As a consequence of this high tectonic stress, the area is affected by continual earthquakes, some of which attained Richter magnitude values of 8 or 9 (fig. 2).

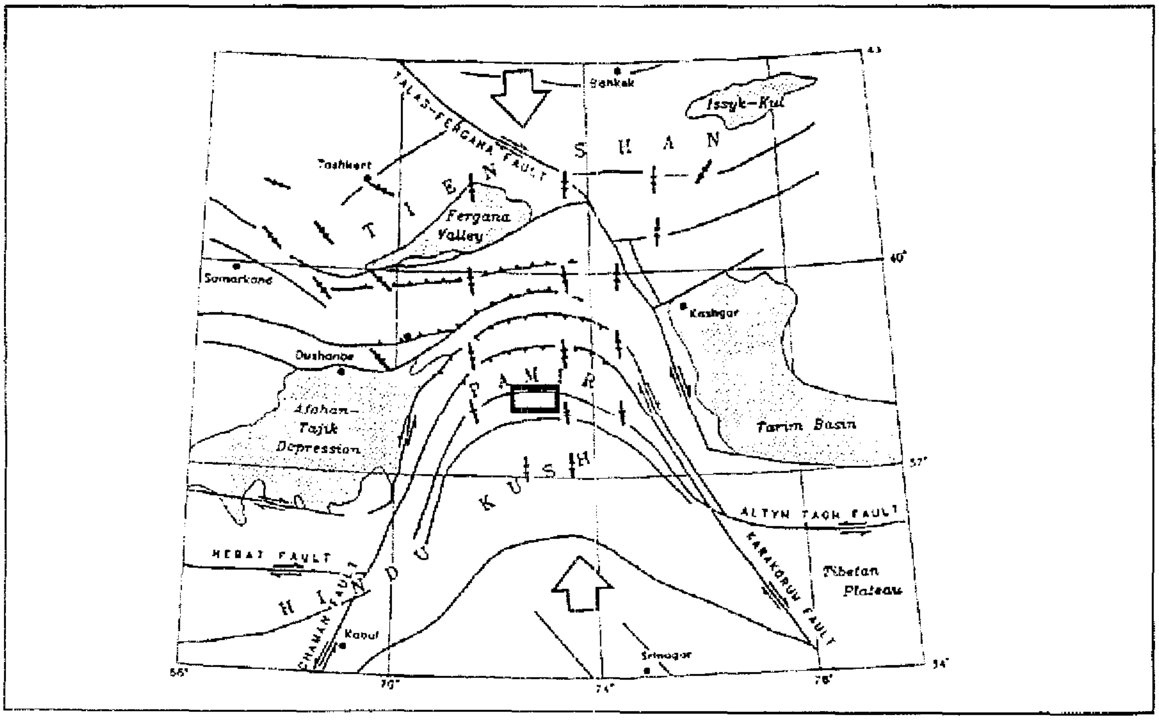

Fig. Tectonic framework of the Pamir Mountains including the Lake Sarez area (from Lukk et al.; Lake Sarez is situated in the EW rectangle near the centre of the map.

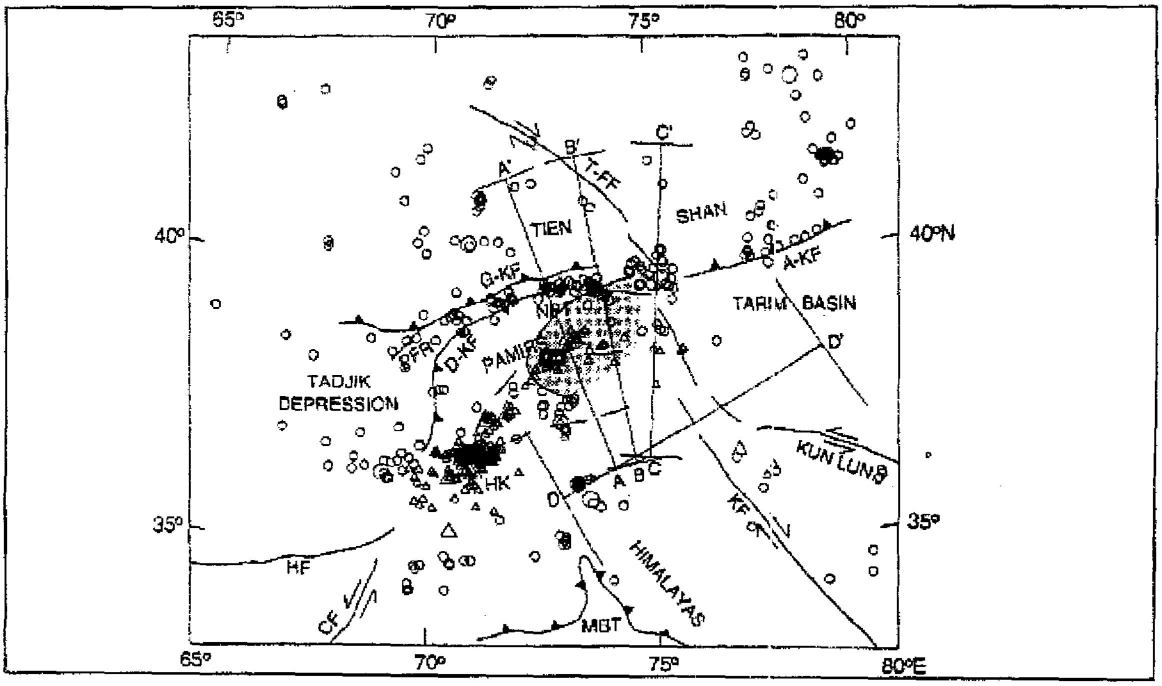

Fig. 2. Epicentres of earthquakes in the surroundings of the Pamirs with location of the Lake Sarez area (from Fan et al., 1994).

3.2 Field visits

Six days were spent in the field with Tajik colleagues, Dr. Anatoly Ischuk and Col. Yusuf Akdodov. The Usoi dam was studied for three full days; the critical unstable slope ("Pravoberezhny slope") on the right bank of the lake, just opposite the base camp, was ascended to an elevation of about 3,900 m; and other slopes along the western part of the lake were inspected visually from a boat. Boat transport was an irreplaceable help in reaching critical locations quickly. The discussions held during the field visits and during two meetings organized in the camp were highly objective and fruitful.

3.3 Findings

3.3.1 General geotechnical conditions

The highly active tectonic regime causes intense stress in the rock mass, resulting in excessive fracturing and the formation of abundant shear zones, mega-joints, and cleavage (photo 4). In extreme cases, the rock mass is completely crushed or mylonitized. For geotechnical assessment of slope stability, this signifies the following:

- The high degree of fracturing has led to continuing rock fall and extreme talus formation along the slopes (photo 5). These talus slopes have an angle of repose of 35-40 degrees, which represents the approximate angle of internal friction of the fragments constituting the talus mass;
- The structure of the rock, with its original bedding or foliation planes, is of secondary importance only because, apart from the potential failure surfaces along the bedding, there are always sufficient other internal surfaces available to serve as foci of rupture for landslides. Therefore, principally all steep slopes are more or less landslide-prone;
- In many cases it is rather difficult (if not impossible) to distinguish between disturbed and crushed rock resulting from (1) tectonic stress and (2) former large-scale landsliding processes. This could be the reason for

controversy on the size of old landslide bodies along the flanks of Lake Sarez (State Committee on Emergencies, 1997, and Prof. Anatoly Ischuk, Institute of Earthquake Engineering and Seismology, personal communication).

3.3.2 Usoi landslide dam

3.3.2.1 Dam formation

The Usoi landslide dam was formed in 1911 by a huge earthquake-triggered rock slide ("Bergsturz," as defined by Heim, 1932), which blocked the valley of the Murgab River. The total volume of the slide has been estimated at about 2 km^3, and the maximum height of the dam above the valley floor is about 600 m. The main constituents in the visible parts of the dam consist of quartzites and schists (Carboniferous age) and marbles and shales (Permian-Triassic age) with some secondary gypsum, anhydrite and dolomite.

The location of the source of the Usoi rock-slide failure was apparently determined by the combination of a series of very unfavourable tectonic factors:

(1) The generally high degree of rock fracturing from former tectonic movements,
(2) The presence of a major thrust fault (photo 6),
(3) The presence of a series of intensive shear zones forming the necessary geometric setting for a typical wedge failure (fig.7 and photo 8), and
(4) The presence of a SW-NE-trending active wrench fault in the innermost corner of the wedge (photo 8)

3.3.2.2 Physical characteristics of the dam

The landslide has been divided into several parts consisting of individual massifs, each of which has its special features in regard to structure, size of blocks, amount of fines, etc. (State Committee on Emergencies, 1997, 1999). These massifs are

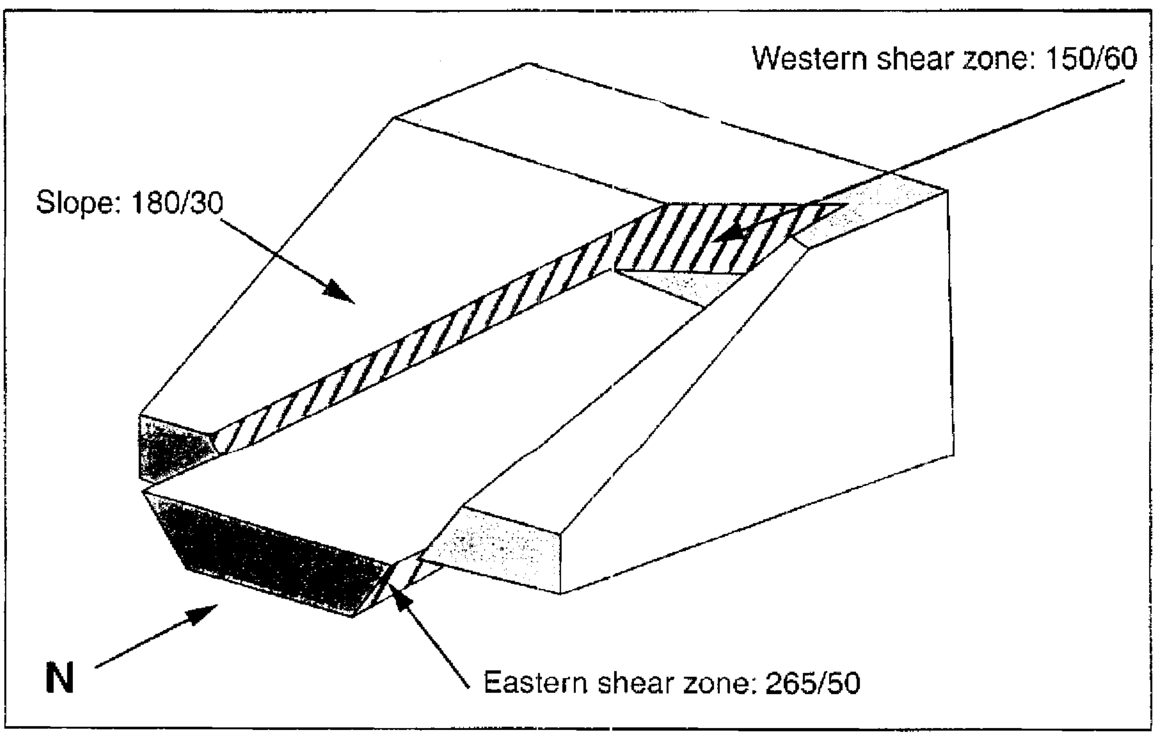

Fig. 7. Simplified scheme of initial wedge failure of the huge Usoi landslide ("Bergsturz"). Tow shear zones form a wedger with intersection line oriented 214/38. The baseline of the wedge is not shown in this model.

interpreted to represent several short intervals during the landslide catastrophe. The upstream area of the dam has been divided into three sectors with different physical characteristics:

- *Southern sector:* This is the highest part of the dam with a maximum height of about 270 m above lake level. The surface is covered by blocks of various sizes, the largest with a diameter as great as 20 m. Almost no fines are visible on the surface.

- *Central sector:* This part rises on the average approximately 100 m above lake level and has a distinct border towards the right part, where the surface is lower. The surface in this central part differs from that of the rest of the dam in that there are no large blocks, and the surface includes a large amount of fines (silt) There are clear indications that this material originated from surficial colluvial deposits on the slopes before the landslide occurred. The surface is extremely irregular and several cracks or openings in the ground exist. The downstream part includes large fragments of more-or-less undisturbed rock (photo 9).
- *Northern sector:* This is the lowest part of the dam, with a minimum freeboard of approximately 50 m. A continuous surface from the lake to the downstream side is covered by large blocks; the largest diameter of these blocks is approximately 20 m and the average diameter is estimated at 2-5 m (photo 10). Practically no fines are visible. In the area closest to the source of the old landslide there are active rock avalanches, debris flows, and mudflows (photo 10). Today, these flows are directed towards the lake. One of the rock avalanches apparently has diverted sediment transport from the slope above the downstream side towards the lake

Along the downstream face of the dam, a large flood plain of fine debris-flow material has been deposited since formation of the dam (photo 11). This deposit of debris-flow material is resting partly on the blocky dam material; the depositional mass is terminated by a local canyon on the downstream face of the dam, which has developed due to erosion by the seepage springs that flow from the dam.

Finally, it should be emphasized that the enormous proportions of the dam and its various features can be comprehended only by an extended visit to the area.

3.3.2.3 Geotechnical stability of the dam

There are two types of stability that need to be addressed: (1) the stability of the entire dam mass and (2) the local stability of its slopes

3.3.2.3.1 Safety against sliding of the entire mass of the dam

The entire dam mass is subjected to the hydrostatic load of 500 m of reservoir water. This load could cause a sliding failure along a sub-horizontal surface beneath the dam, either between the base of the dam and the original ground surface or at greater depth. The controlling factors are the hydrostatic load acting on the dam and the frictional resistance beneath the dam. The hydrostatic load can act on the upstream face as in a CFRD (concrete-faced rockfill) dam or on the central core, as in a traditional earthfill dam. Because the internal structure of this landslide dam is unknown, the simple CFRD case is used here in a rough stability estimation: the longitudinal cross section of the dam can be simplified as a triangle with a baseline 5,000 m long and a height of 550 m, impounding a lake with a depth of 450 m (fig. 12). The specific weight of the dam material is estimated at 22 KN/m^3.

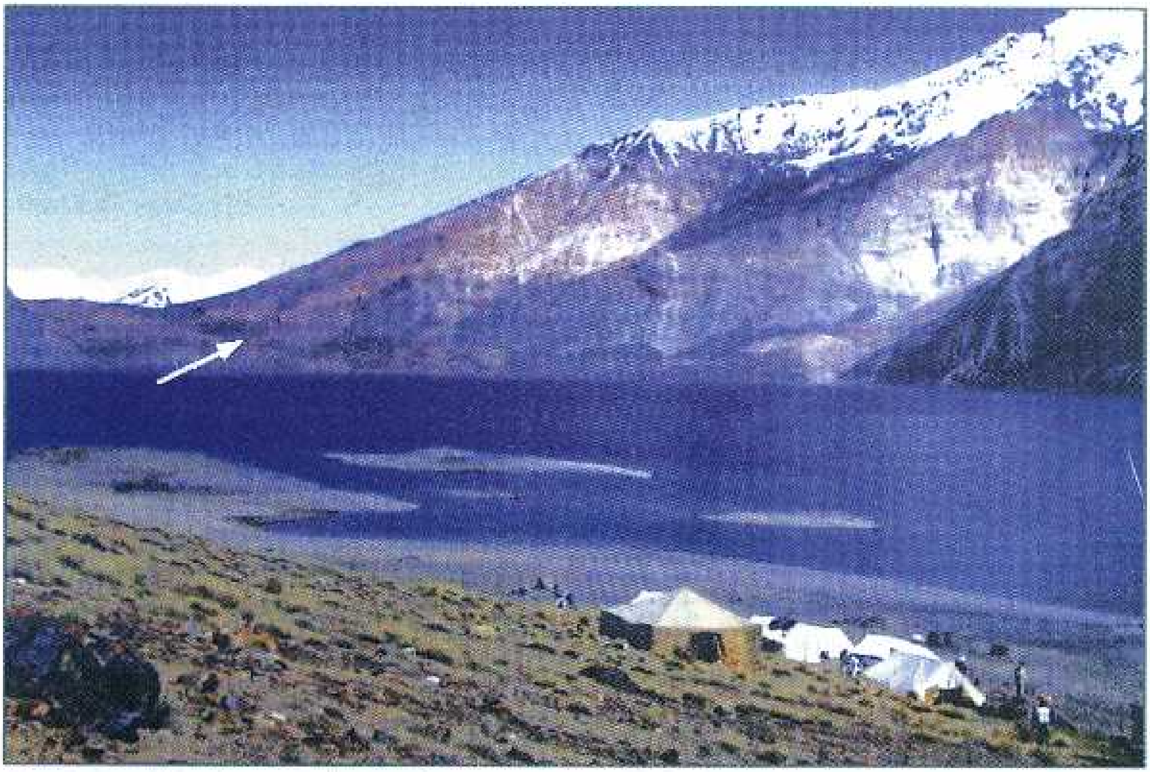

Photo 3. General view of western Lake Sarez showing the base camp in the foreground, the enormous damming landslide mass (arrow), and the huge scarp of the 1911 landslide in the background to the right. Photo credit: Jörg Hanisch

Photo 4. Example of intensely fractured rock (within the "Rushan-Pshart Thrust Fault Zone"). Photo credit: Jörg Hanisch

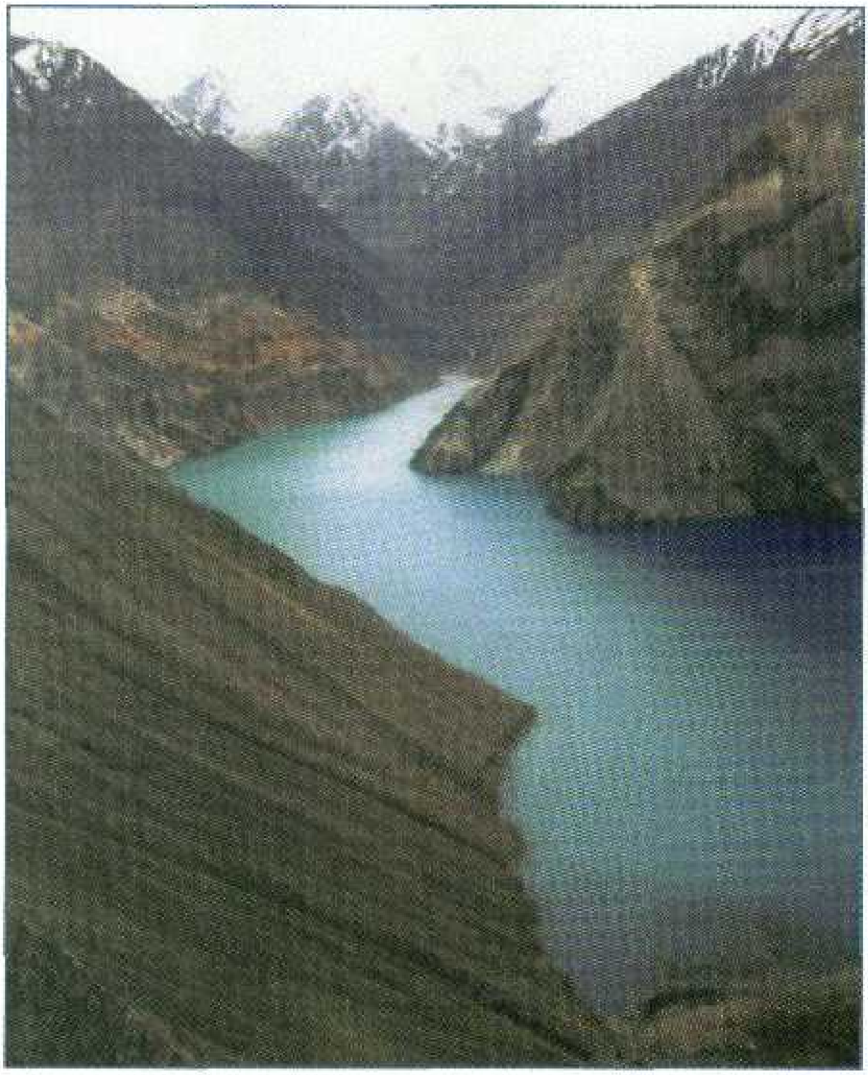

Photo 5. Extensive talus formation (lower left) at Lake Shadau, a tributary lake dammed by the Usoi landslide. The "Shadau Thrust Fault" is in the background (marked by reddish-brown, "bright" zone to the left). Photo credit: Jörg Hanisch

Photo 6. Westernmost part of the Usoi landslide scarp with a regional thrust fault (arrow) between Carboniferous schists and quartzites (below) and Permian-Triassic shales (above). Blocky material of the northern part of the dam in the foreground abuts against finer material of the middle part (left). Photo credit: Jörg Hanisch

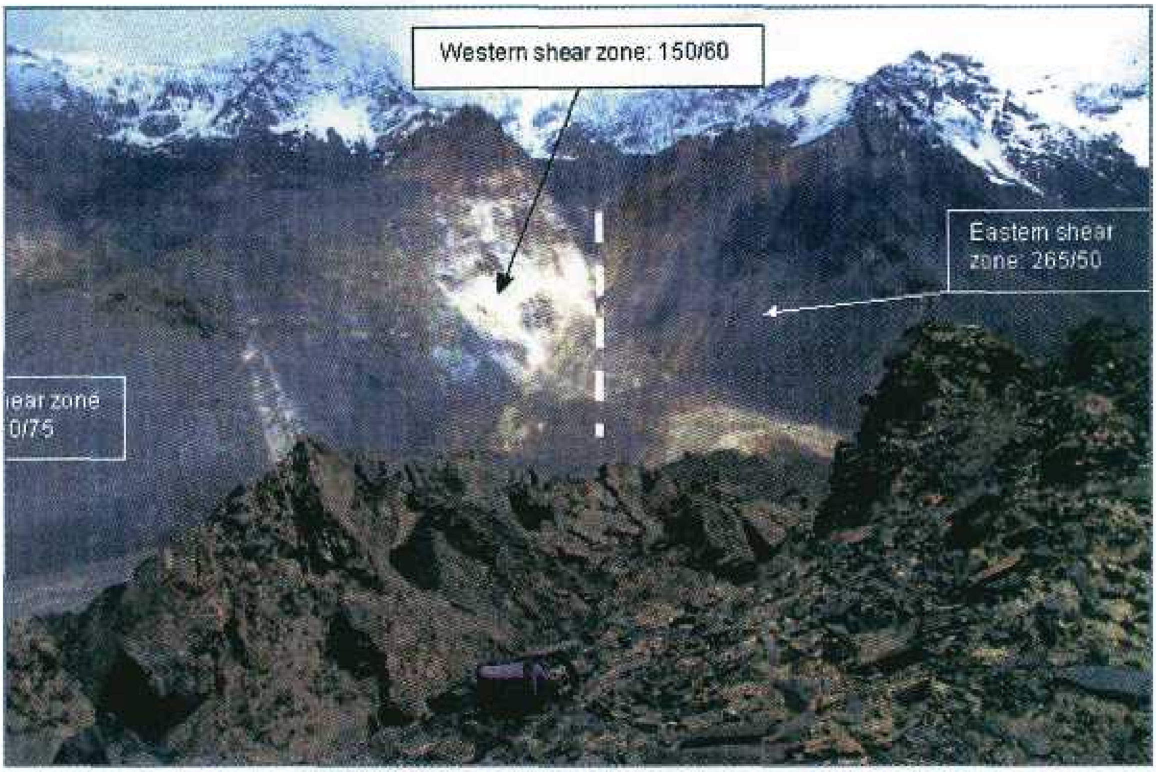

Photo 8. View from the high central part of the Usoi dam (camera bag for scale) to the scarp from which the huge landslide originated. Two shear zones to the left and right of an active wrench fault (subvertical line) form a wedge of failure. A huge debris cone has formed since the landslide occurred in 1911. Another pronounced shear zone follows to the left. Photo credit: Jörg Hanisch.

Photo 9. Huge, rather undisturbed rock block (dashed line) within the central part of the dam. This block was displaced by a secondary landslide (scarp is immediately behind the blocky material near the crest line of the dam). Photo credit: Jörg Hanisch

Photo 10. Rock avalanche deposit lying upon a debris-flow cone (in the foreground) and abutting against blocky, dark grey dam material to the left. The scarp of the 1911 landslide is in the background. Photo credit: Jörg Hanisch

Photo11. View to the downstream side of the dam (dashed line) with the debris-flow "flood plain" in the centre. The erosional channel ("canyon") at the terminus of this flood plain cuts partly into these recent fluvial deposits (left arrow) and slightly into the dam material itself (right arrow). Photo credit: Jörg Hanisch.

The effective weight, W_D, of a 1-m-thick slice of the dam can be calculated as follows:

$$W_D = W_{D1} + W_{D2}$$
$$= (F_1 \times \gamma_{eff} + F_2 \times \gamma) \times 1\ m$$
$$= (1.1 \times 10^6\ m^2 \times 12\ KN/m^3 + 0.275 \times 10^6\ m^2 \times 22\ KN/m^3) \times 1\ m$$
$$= 13{,}200\ MN + 6{,}050\ MN$$
$$= 19{,}250\ MN$$

where γ = unit weight above the water table
γ_{eff} = unit weight below water table
K = thousand
M = million
N = Newton

The friction force, F, which resists the force of the water, acts along the base of the dam. This force depends on the weight of the dam and the resisting angle of internal friction, φ, between the dam and its base, which is assumed (conservatively) to be 25°; cohesion is considered to be minor, and is neglected.

$$F = W_D \times \tan \varphi$$
$$F = 19{,}250\ MN \times 0.466$$
$$\approx 9{,}000\ MN$$

The water load, L_W, on a slice 1m thick averages (as a rough estimate) 2.25 MN/m^2 between the lake surface and a depth of 450 m. This force acts against the vertical component of the slope area of 450 m^2 (fig. 13) as follows:

$$L_W = 2.25\ MN/m^2 \times 450\ m^2$$
$$\approx 1000\ MN$$

The factor of safety, FS, is the quotient of the resisting friction force and the horizontal water load:

$$FS = F / L_W \approx 9$$

Seismic shaking due to a strong earthquake could reduce this safety factor by as much as 50 per cent (cf. next paragraph), resulting in what is still a high safety factor of 4.5.

The Usoi landslide dam thus has a more than satisfactory stability against sliding of the entire dam. Furthermore, the previous morphology of the valley had pronounced surface relief because of the tributary valley from the south, which is now filled by Lake Shadau (photo 5). Therefore the supporting foundation for the dam is undoubtedly quite rugged, a factor that will resist sliding along the foundation. In addition, the valley narrows considerably at the downstream face of the dam; thus, each of these topographic factors will considerably increase the force that resists sliding. Altogether, the stability of the dam as a whole is very high. In addition, future earthquakes will tend to readjust the dam material, leading to a somewhat higher degree of compaction.

From a geological point of view, the long-term stability of landslide dams can be assessed from the evidence of geological records. As mentioned by the State Committee on Emergencies (1997, 1999), there is evidence of several former major landslide dams in the Murgab valley. Terraces of former lake sediments existing at various levels along the flanks of the valley demonstrate that some of these dams persisted for several thousand years and that the lakes had totally filled with sediment.

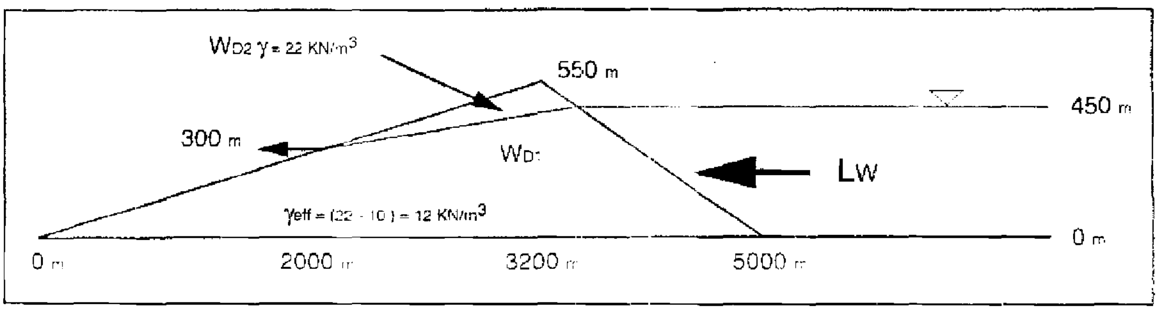

Fig. 12 Scheme for the formulation of the general stabily of Usoi landslide dam against the hydrostatic force (water load) of Lake Sarez.