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HAZARD ASSESSMENT OF LAKE SAREZ ROCKSLIDES AND USOY DAM IN PAMIR MOUNTAINS (TADJIKISTAN)

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ROCKSLIDE AND FLOOD RISKS

Lake Sarez is the result of an earthquake triggered collapse which in 1911 threw about 2 km^3 of rock in the Murgab Valley from its right flank. The dam that resulted from this event (called Usoy dam from the name of the buried village) has blocked the Murgab river and led to the formation of Lake Sarez (from the name of the drowned village) which now extends over a length of more than 60 km. Usoy dam is built by the local Sarez Sandstones, limestones and gipsum. The dammed water with a maximum depth of 500 to 600 m is infiltrating into the coarse landslide blocks. The threat of Usoy dam and Lake Sarez definitely resides in the risk of a sudden dam rupture and flooding of Murgab and Bartang Valley down to Rushan and Amu-Daria river.

USOY DAM AND WATER LEVEL INCREASE OF LAKE SAREZ

During the first years of water level increase, the dam was as good as impervious up to a level of about 3170 m a.s.l. where the discharge through the dam body was about 5% of the maximum discharge observed in September 1973 (lake level at 3273 m asl). Since the lake level exceeds 3170 water flows through the dam with various discharges, depending on lake level, increasing to 50% of the 1973 discharge up to level 3225, remaining unchanged between 3225 to 3260, then strongly increasing to the value of 1973. The present total visible discharge by the springs on the downstream slope of the dam is of 33 to 80 m^3/s (Figure 1).

This discharge is at the origin of a marked erosive process which led to the canyon, carved in fine sedimentary material deposited after the main collapse, on the down-slope side of the dam by the Usoydara river which presently flows in the wedge of the 1911 collapse. This canyon is oriented sub-perpendicular to the dam axis in the fine sedimentary material, and abruptly turns NE at the contact with the dam material to become parallel to its downstream slope. This clearly indicates that the erosion cannot cut its way through the coarse material of the dam body and has therefore been deflected.

A dam rupture can occur due to intrinsic instability of the dam body or by internal erosion. The discharge of Lake Sarez through the dam body is massive and implies probable phenomena of internal erosion which may have led to settlements of the dam crown. Dye tests executed in the frame of former Russian investigations, mentioned water-flow velocities through the dam body of up to 6 m/s. Since these velocities appeared unbelievable compared to usual orders of magnitude, they had to be checked to be sure to evaluate this risk in full knowledge of the problem. This was even more necessary as some topographic surface features of the dam body showed characteristics that could theoretically be due to such a process.

The springs in the Murgab Canyon are moving upwards and a pessimistic scenario is including a regressive erosion of the dam. The worst case for a sudden process is based on massive overtopping by a landslide incuced wave on Lake Sarez. This scenario includes a sudden destruction of the 3.7 km long dam crown and a failure on the Murgab side. The base length along the former Murgab river bed is approximately 5 km and perpendicular to this direction a large line of 4 km is blocking the stream. The safety of the dam body regarding intrinsic instability has been verified by various authors, even taking into account the high seismicity of the region. Actually no signs of failure are recognised at the dam.

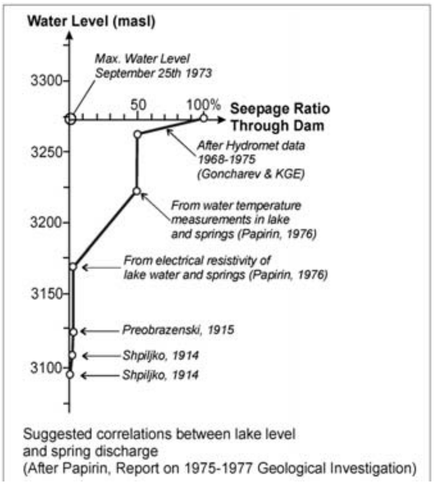

Figure 1 - Lake Sarez water level and discharge of Murgab river from 1914-75. The discharge increases with a rising lake level, but also in function of the dam permeability

USOY DAM OVERTOPPING

The present freeboard of the dam is of some 50 m and the mean water level increase is now of about 10 cm/year. The annual fluctuations of the water level are comprised between 10 and 12 m.

As there is no reasonable scenario which could lead to a massive change of the inflow rate into Lake Sarez and assuming that the permeability of the dam body will not suddenly decrease (e.g. by clogging of a major part of the watherpaths as a consequence of an earthquake), then the curve of the water level increase of the lake shows that there is no short time threat of overtopping of the Usoy dam connected to such causes. This is especially true as latter's permeability increases from base to top (especially above 3260 m), and that obviously a quasi-equilibrium is already reached. Anyway a progressive overtopping in correlation with the present annual mean water level increase is even possible but not probable.

In absence of intrinsic instability, regressive erosion of the canyon, and apart from the said risk of internal clogging, analysed in former reports, or erosion which will be discussed later, the remaining problem to be resolved for Lake Sarez resides therefore in the risk of a massive overtopping of the dam, and its correlated erosive ruin. Such a phenomenon can only be imagined by mean of a wave induced by a huge landslide (earthquake triggered or not), like it has occurred on a smaller scale for the Vajont dam in Italy in 1963.

LANDSLIDES ON THE RIGHT BANK OF LAKE SAREZ

The Right Bank of Lake Sarez within the studied area belongs to the complex anticline of the Muskhol Range, who's axis follows approximately the E-W direction. On the base and on the top of the Right Bank the detritic Sarez Formation is predominantly built by sandstones. In the middle part of the Sarez Formation detritic shales and very fine sandstones are abondant. The measurements on Right Bank Slope (RBS) have shown a predominant NE-dip of the main bedding, the dip is ranging from 10° to 30°, even if locally sub-vertical structure could be observed. The mentioned tectonic lines and a density of fractures results in a high potential of rupture lines within the bedrock. The rocks are often crushed and the rockfall processes are frequent in the cliffs.

The landslide of the Right Bank Slope (RBS) can be divided into four zones with specific geologic conditions and different slope processes: South, Central, North and Upper Parts.

The South Part is the rockslide with the highest activity on RBS. The disruption niche is well defined and fresh. The niche is lying at 3600 m.a.s.l. and affects loose material and bedrock. The stratification in the dislocated rock mass itself is uneasy to determine and lateral variations are identified. A volume of 0.1 km^3 is sliding on a surface with 40 to 60° and a sudden rupture is always possible. The rockslide mass is dismantled intensively and blocks are frequently falling down to Lake Sarez.

The Central Part shows similitude with the South Part. The similitude resides in its extension and volume, being restricted upwards by an upper limit in alignment with the main disruption niche of the South Part. The difference is that this Central Part is not as active. The displaced mass composed by Sarez sandstones presents less fractures and a lower degree of dislocation than the South Part. Field observations have shown evidence that it is an old rockslide, which has not been reactivated recently but with similar mechanism. Topographic conditions in this area are more favourable than in the South part, especially when slip surfaces are less inclined to reach the bottom of Lake Sarez. The risk of reactivation is lower than in the South Part, but in case of a major slope rupture this Central Part will loose resistance.

In the North Part of RBS a large mass without activity has been identified. The topographic conditions differ strongly from those of the South and Central Parts, not only above lake level but also below. Maybe this mass moved before the last glaciation, because there are no evidences for an activity since this period. Field observations have shown a bundle of indications for a stable mass, especially a moraine sediment on the lower slope of the North Part.

The Upper Part of RBS is dominated by landslides and rockglaciers. Both processes are related and gravitational forces from the rockfalls and rockglaciers are influencing the landslides below. Those processes are easily recognised in the loose cover material. It is very difficult to identify the instabilities of the bedrock. Snow melt and rainfall water is directly infiltrating in coarse gravels and blocks of sandstones. There are no hydrologic lines at the surface of the Upper Part. Further rockglaciers furnish water which is also unfavourable in terms of stability.

Landslides thickness of more than 100 m have been distinguished. The instabilities are affecting loose material and relaxed bedrock. Above 3700 m a.s.l the most parts of RBS are covered by rockglaciers. Most of them are reaching the landslides below and they are overloading the ongoing processes. The observed forms of the rockglaciers were fresh and the ice found in the debris is proving an active process. Some of the geodetic points of former networks are located on the permafrost area. This means, that the displacement values are not significant for the landslides on RBS. Most of the geodetic points were placed on rockglaciers, in superficial landslides or on unstable blocks. The results of the geodetic measurements are for this reason doubtful. The melting ice and snow of the rockglacier area is partially infiltrating the underlying landslides and again influencing the activity. This seasonal phenomenon with melting water is probably controlling the intervals of the displacements. Rockfalls are frequent in altitudes above 4300 m a.s.l. and below 3600 m a.s.l. In the Upper Part the source area is located in the steep slopes reaching 4500 m.a.s.l. Rockfalls are not significant for the worst case scenario.

GEOLOGICAL MODEL FOR THE RIGHT BANK OF LAKE SAREZ

Former Russian works contain a lot of different scenarios with landslide volumes ranging from 0.3 to 2 km^3. Russian geologists were considering a landslide mass with 200-300 m of thickness including the whole processes of rockslides, rockglaciers and landslides inside the loose debris. Considering the field measurements, the topographical and geological conditions, the scenario with 200-300 m thick landslides on RBS is not realistic. The conditions are not similar to the Usoy collapse which occurred in 1911, especially the tectonic pattern is not comparable. The activation of landslides with a thickness of 300 m needs to cut very deep into the resistant rocks. The topography at the foot is flatter, especially in the North Part. For this reasons a high energy is needed to overcome the intrinsic resistance of the rocks. In comparison to the "former" Russian hypothesis, the "new" Swiss results based on the field investigation are considering a landslide volume of 0.5 km^3. This mass is identified in the field and corresponds to a real mechanism of the Right Bank Slope. The volume of 0.5 km^3 is comprising the landslides, the rockslides and the rockglaciers. Processes, who are not visible from the surface or mechanisms without deformation horizons can not be included in a landslide scenario with high probability.

SCENARIOS

The Right Bank Slope is dominated by many fractures. The lower part of the slope is divided into three compartments. The South, the Central and the North Part can be distinguished. Each of these compartments can break in several volumes into a succession of smaller rockslides. A monolithic instability is not realistic, but a serial destabilisation is still possible as a worst case scenario. After the collapse of the lower slope, some landslides of the upper part, reaching the rockglaciers would probably follow by regressive processes. Some actual tension cracks on reduced areas are a result of this relation between the masses. The destabilisation would concern the loose cover material, eventually with parts of the fractured bedrock.

Summarising the mechanism and the potential destabilisation the most probable scenario follows following steps:

- rockslide in the south part: this event will involve at least three rock masses; a monolithic movement is not realistic
- regressive destabilisation of landslides in the loose material above the south niche
- rockslide in the central part, this more improbable event could eventually move as a monolithic block
- destabilisation above the central niche, landslides in loose material and destabilisation of northern border including rockslides of Sarez formation
- landslides and rockslides affecting the upper part of the slopes, including the permafrost area.

This five steps are considered as worst case scenario. More probable are the first steps. The scenario is depending on the magnitude and the interval of the considered earthquake.

CONCLUSIONS ON THE LANDSLIDES OF THE RIGHT BANK

Former results concerning the landslide on the Right Bank of Lake Sarez were based on monolithic collapse of 2 km^3. Recent investigations in the field lead to a different interpretation of the mass movements. The Right Bank Slope (RBS) is affected by rockslides in the South and the Central Parts. On the Upper Part landslides are active, but they are less than 100 m deep. The most part of the upper slope is a permafrost area. Large rockglaciers are moving down to 3700 m a.s.l. These rockglaciers are dominated by seasonal icemelting and they control the activity of the landslides in the loose material.

All identified processes together represent an estimated volume of 0.5 km^3. Rockslides, landslides in loose material and rockglaciers can't be destabilised at the same time for a monolithic event. This masses will be activated step by step in function of the mechanism and following geological borderlines. With respect to the different types of instabilities it is not realistic to take into account a monolithic landslide with a collapse of 1-2 km^3. The estimated height of a landslide triggered wave must therefore be reviewed strongly downwards.

The identified mass movements are of much smaller volume than described before. Some of the landslides are just superficial, that's why a monitoring is not significant for a deep movement. As a consequence the geodetic measurements in the past century are doubtful. The new network should take into account the different mechanism.

HYDROGEOLOGICAL CONDITIONS IN USOY DAM AND FLOOD RISK

In view of the flood risk recent investigations about the hydrogeological conditions of Usoy Dam were planned by a swiss team. After two tracer injections water samples were analysed in spring and summer of 2002. One of the most important questions concerns *the water velocity through the dam*. If velocity is high it can be assumed that the water flows in relatively straight open channels. This involves a certain risk of erosion of the flow paths. On the other hand, low velocity in spite of the steep gradient and the high rate of discharge from the springs would result in sinuous flow paths in narrow channels with a low risk of erosion.

Along the lake shore on the right-hand side of the valley there are several visible infiltration zones. It was impressive to see how the lake water flowed between the large stones and boulders along the shore into the dam and disappeared. There were some places where the inflow was probably low, but two places showed a clearly considerable inflow. These places seemed to be ideal for the tracer injections we planned. The total visible inflow was estimated at not more than 5 m^3/s. Since the discharge of the canyon springs is much higher (28.4 m^3/s), there must be some other invisible infiltration zones.

Water started to filter through only 3.2 years after the creation of the dam. The average water inflow into the lake is 45.7 m^3/s = 1.44 km^3 per year. For the following estimation, evaporation (2.1 m^3/s only) may be ignored. During the 3.2 year period mentioned inflow was 3.2x1.44 = 4.6 km^3. This is only a tiny part of the entire volume of the lake. This means that when the water started to filter through the lake was not yet full. Between 1949 and 1988 the level of the lake rose by 7.2 m, in spite of a continuous discharge through the dam. In accordance with the conclusions concerning the visible infiltration of a few cubic meters per second only, there must therefore be some flow paths below the present level of the lake.

The tracer experiment with Uranine and Fluoresceine was successful, but only a minor part of the tracer were measured in the springs. Uncontrolled discharge through the Usoy dam can be on the right bank or under the spring level at 3100 m a.s.l. In the second case, the water would seep directly into the river bed where measurements are impossible. From Lake Schadau a small discharge can eventually contribute to Murgab river. The two lakes are in fact connected by hydraulic exchange, but due to topographical and geological effects a bigger discharge through the left bank is not considered.

Former reports were presenting groundwater velocity of 6 m/s. Lower velocities are calculated due to the swiss tracer experiment. The tracer passed Usoy dam in 2-3 days, the calculated velocities range from 0.01-0.1 m/s. This new result is still a very high groundwater velocity, but the coarse material with huge blocks from the 1911 landslide and large pores can explain this phenomen.

The tracer experiment shows that the stability of Usoy dam can not be affected by a quick internal erosion. Further, the velocity of the groundwater is so slow, that a Lake level rise through a wave would partially be stopped. The permeability for a faster discharge is not given. As a consequence, the wave would be stopped partially and the danger is lower at the foot of Usoy dam and at Barchidiev.