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LAKE SAREZ RISK MITIGATION PROJECT: A GLOBAL RISK ANALYSIS (*)

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1. INTRODUCTION

Lake Sarez in Tajikistan was formed in 1911 when a massive earthquake-triggered landslide buried the village of Usoy under a 650 m high obstruction which dammed the Murghab River. The resulting 60 km long lake containing over 17 km^3 of water is located behind the so-called Usoy natural dam in the Pamir range, the highest dam in the world.

Although the safety of the lake has been studied over many years, significant gaps and inconsistencies existed in the data available. Despite this lack of data, however, it is clear that the risk to the downstream population living in the Bartang and Pianj river valleys remains high [1]. The following actions have been required to mitigate the risk in the framework of the so-called Lake Sarez Risk Mitigation Project (LSRMP):

1. The design and implementation of a monitoring and an early warning system in order to follow up the long term evolution of the natural

(*) *Le projet de réduction du risque relatif au lac Sarez: une approche globale de l'analyse du risque* structures as well as to reduce the consequences of any uncontrolled behaviour of the dam (Component A)

2. Identification and construction of safe havens as well as training the vulnerable downstream communities under the disaster preparedness programme (Component B)
3. The preliminary studies of long term solutions to minimise the probability of failure (Component C)

The article presents the main results of the studies performed in the framework of a risk analysis approach carried out for Components A[1].

2. LAKE SAREZ AND USOY DAM

Numerous studies have been conducted since the Usoy collapse in 1911. These studies provided essential information and analysis in the various domains involved such as seismology [2, 3, 4], geology [5, 6, 7], hydrology [8], hydrogeology [9] , hydraulics and dam engineering [10].

In the framework of the LSRMP an in-depth analysis of the available data, the collection of complementary data in digital format as well as additional field visits and investigations enabled a better understanding of the situation and global view of the phenomena involved.

2.1 GEOLOGY

The Usoy dam presents a typical cross section with an overall upstream slope of 1/3 and a downstream slope of 1/7. It is composed of two basic material types:

- Carboniferous shales and sandstones, ranging in size from tens of metres to tens of centimetres. This zone occupies the surface of the central and left side of the dam and represents the first waves of the landslide.
- Triassic material with size ranging from metres to centimetres, set in a matrix of sandy silt. This zone occupies the surface of the extreme right abutment of the dam (origin of the collapse) and represents the last waves of the landslide

1 Financed by the SECO, Bern, managed by the WB, Washington for the Ministry of Emergencies and Civil Defence, Dushanbe.

The internal composition of the Usoy Dam remains unknown. According to surface observations, huge and abrupt variations in granulometry are to be expected. Some geophysical investigations have been performed, but their interpretation is doubtful due to the complexity of the internal structure and the absence of calibration by in-depth investigations.

Fig. 1
Lake Sarez and Usoy dam from left bank: the whitish zone corresponds to the origin of the collapse
Lac Sarez et barrage d'Usoy depuis la rive gauche: la zone plus claire correspond à l'origine de l'effondrement

The debris fan of the temporary stream that used to flow from the collapse zone along the right abutment into the Murghab river downstream of the dam up to the 1940's and presently to the lake, is composed of a majority of fine-grained material. The debris fan shows a far lower permeability than the dam material described above: the material ranges from cobbles to silt.

About 45 springs flowing from the downstream face of the dam form the Murghab river. The majority of the springs which constitute the visible part of the discharge of Lake Sarez through the dam by seepage is located at the head of a canyon (infiltration zones can be observed on the upstream face of the dam, near the right bank). The fact that all major springs are located approximately at the same elevation (about 100 m under the lake level) shows that the lower 400 m of the dam -or at least of its core- has a far lower permeability than the upper part where the seepage takes place. This difference in permeability is closely related to the mechanism and to the history of the Usoy collapse.

Some 4 km upstream of the Usoy dam, a large unstable slope has been identified and is referred to as the so-called Right Bank Landslide (RBL). The slope is mainly covered with loose material (silty-sandy-blocky material resulting from the weathering of the bedrock, and some glacial till deposits). This loose material shows a certain cementing due essentially to the hard climatic conditions. The bedrock which outcrops mainly along the lake shore is weathered and highly dislocated. It consists of hard and fractured detritic carboniferous rocks of the Sarez Formation (sandstones, schists, slates,…).

This right bank slope shows various indices of instability. The most obvious of all is the lower rock-mass whose volume is estimated at some 100.10^6 m^3. The displacements so far measured are slow (10 to 15 cm/year) and appear to be rather persistent.

Fig. 2
Right Bank slope (RBL) some 4 km upstream of the Usoy dam.
Masse instable de la rive droite, environ 4 km à l'amont du barrage d'Usoy

Geoseismic investigations have been made on the right bank slope. However, their interpretation has not been calibrated with reliable verified data. The only existing borehole has not delivered sufficient precise information for that purpose, restricting the output of the investigations to assumptions.

Actually, there is still nothing known about the third dimension of the potential instability, that is, its depth. As a result, the volume of the potentially unstable mass is still uncertain but reasonable assumptions can be made.

2.2 SEISMOLOGY

Tajikistan is located in one of the most seismically active regions of the world. Large earthquakes have been reported both in historical records and in technical documents originating from the period of instrument records. Tajik experts elaborated several reports which give useful background information on general tectonics of the area and also provide records of earthquakes instrumentally recorded in Tajikistan between 1911 and 1995. Engineering seismological parameters (peak ground accelerations) necessary for the stability assessment of Usoy dam and the Right bank landslide have been derived from these previous studies.

In order to assess peak ground accelerations at Sarez, PSHA and DSHA methods have been applied to earthquake databases which cover a period from 1909 to 1995. PSHA has been based on average focal depths and average focal distances for the defined seismic zones of Tajikistan. DSHA has been applied to assess peak ground accelerations for the upper bound magnitudes based on the 1911 Sarez earthquake. Although some doubts are expressed about the completeness of the earthquake catalogues and the focal depth of the 1911 earthquake, the following conclusions of the analyses can be presented:

- For earthquakes with return period of around 100 years, mean peak ground acceleration of 0.2g has been obtained by PSHA.
- A maximum credible earthquake of M=7.9 with the same focal depth as the 1911 earthquake is likely to generate an average mean peak ground acceleration of 0.21g at the site. This acceleration corresponds to an earthquake with a return period of just slightly above 130 years.
- Based on mean PGAs obtained, it is likely that the earthquakes with return periods >100 years and peak ground accelerations >0.20g are physically almost impossible to occur close to the Sarez, as there will be saturation of earth crust strains and therefore accelerations of 0.2g – 0.21g are likely to be the upper bound mean accelerations.

From the database available, it is noted that the earthquakes generated in the past were deep ones with focal depth >70km. If, however, new earthquakes that may be generated are to have shallow focal depths (<10km), PGA related to the maximum credible earthquake, obtained from attenuation relationships, would be in a range from 0.3g to 0.56g.

2.2 HYDROLOGY AND HYDROGEOLOGY

The average values of precipitations (140 mm/year) are typical of dry climates, with very low averages and standard deviations ranging between 30 and 50 % of the averages. Most of the precipitations occur during the cold season, and rainfall represents only 10 % of the yearly precipitation. Due to the altitude, the average temperature is low (+1°C) with lower values down to –25°C.

For several decades, the outflow (seepage and evaporation) almost compensates the inflow. Hence the average level of the lake rises in time by about 20 cm/year. Presently, a freeboard of some 50 m still prevents any overflow. In any case, the upper layers of the dam are much less compacted and would allow internal flow before overtopping of the crest.

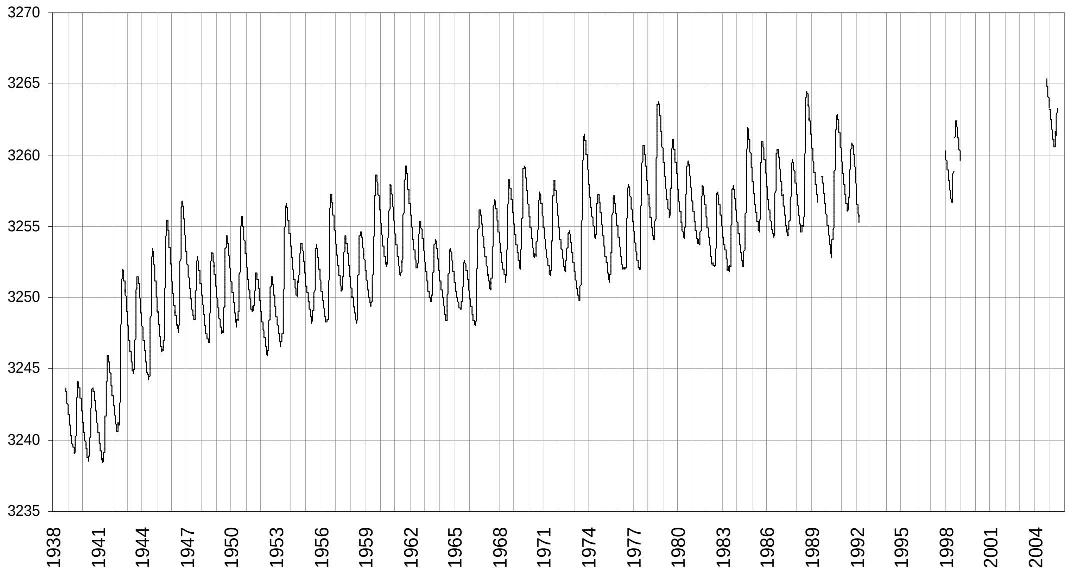

Fig. 3
Evolution of the lake level since 1938
Evolution du niveau du lac depuis 1938

Seepage through the Usoy natural dam began in the spring of 1914, the recorded discharge being 2 m^3/s. From 1940 to the early 90's daily records of the discharge have been performed. The outflow from Sarez ranges from 30 to 80 m^3/s with a yearly average of 45 m^3/s.

The correlation between the seepage rate (outflow discharge) and the lake level is usually very high except when the lake has reached a significant higher level which was never reached before. Unlike normal years, one observes a hysteresis that may explain that during the rising phase of the lake level some perturbation occurred in the preferential internal water paths.

Fig. 4
Head of canyon and springs (arrows) flowing from the lateral edge of the dam
Origine du canyon et sources (flèches) provenant du pied latéral du barrage

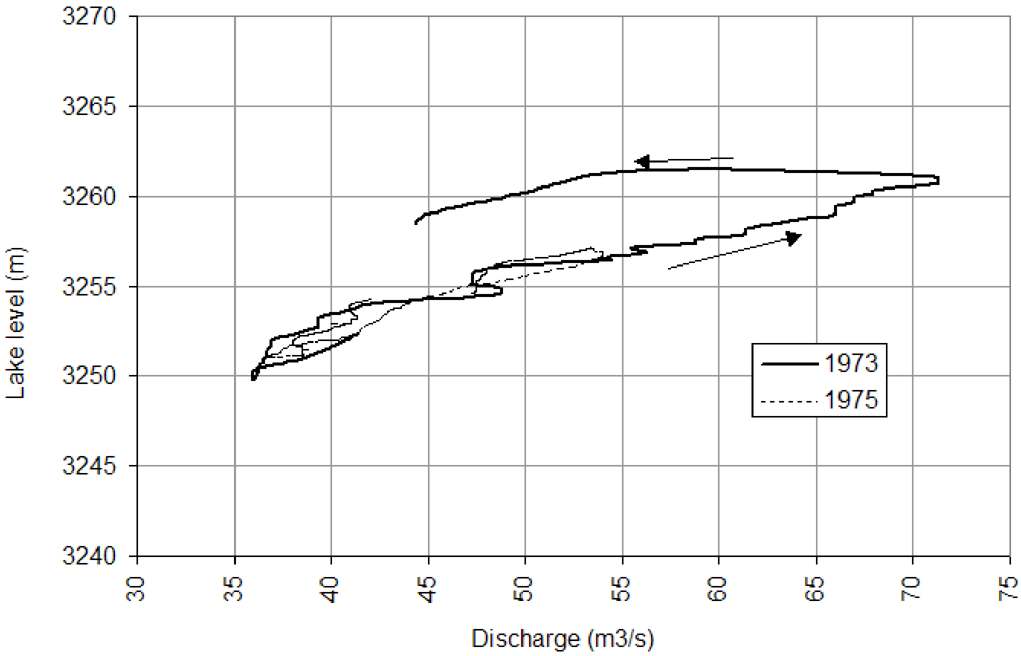

Fig. 5
Hysteresis of the seepage discharge between rising and lowering phases of the lake level in exceptional (1973) and normal (1975) years
Hystérésis du débit de percolation lors des phases de montée et de descente du plan d'eau en années exceptionnelle (1973) et normale (1975)

Due to the width of the natural embankment and the relatively low difference in elevation between the lake level and the outflow springs, the gradient within the dam is very modest (10%). The risk of piping is, therefore, very low.

2.2 WAVE OVERTOPPING

The analysis of the consequences of the collapse of the RBL into the lake Sarez has been made for various hypotheses of the volume of the unstable mass ranging from 100 to 500.10^6 m^3. It was based on a comparative analysis of the waves generated by landslides that occurred worldwide and on numerical simulations. A DEM of the bottom of the lake and of the surrounding shore was used for this purpose.

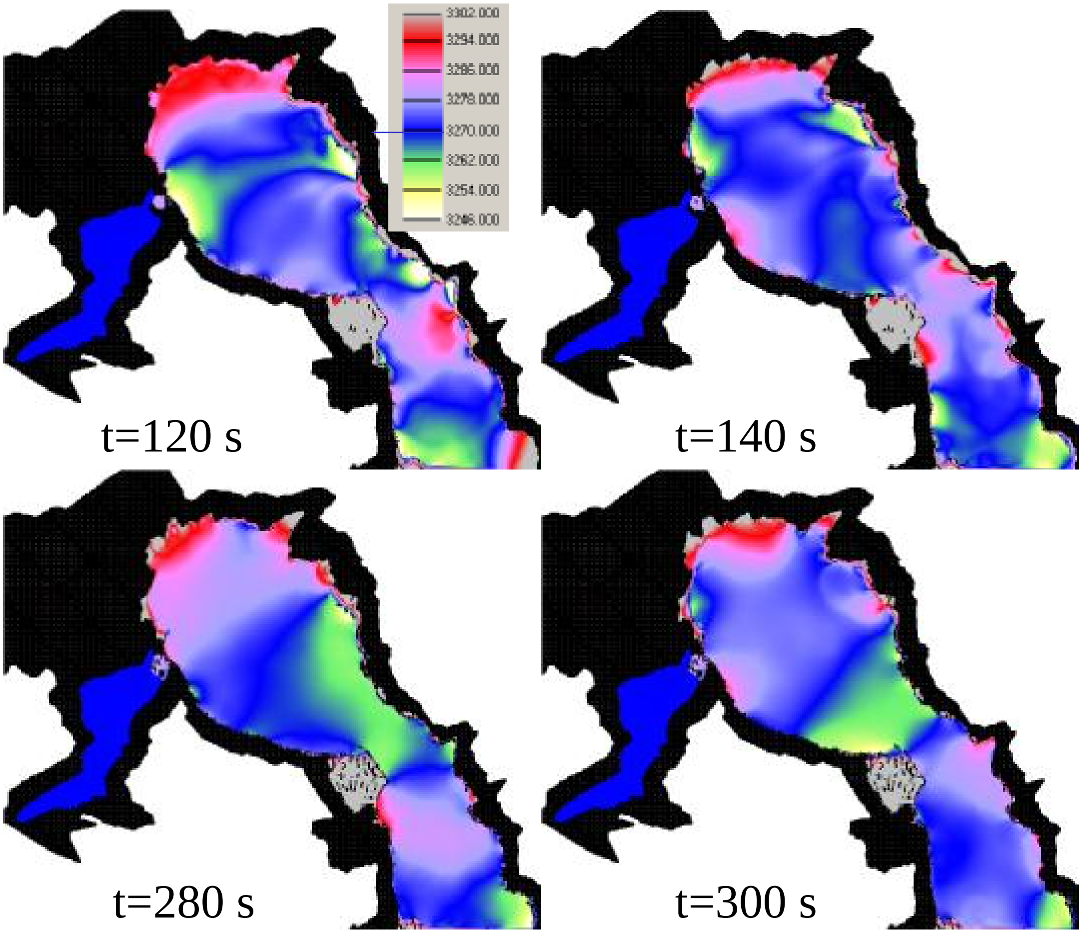

Fig. 6
Numerical modelling of wave propagation in Lake Sarez hitting the dam
Modélisation numérique de la propagation d'une vague dans le lac Sarez à l'encontre du barrage

The analytical results obtained on the basis of comparisons show that for the largest volume, considering that the unstable masses collapse simultaneously, which is highly doubtful, and in selecting the most unfavourable range of parameters, the waves and their run-up induced by the collapse of the RBL would be higher than the dam crest's lowest points by 50 m. However, considering the highly irregular shape of the crest, the volume of water overtopping the crest would be much smaller than 800 000 m^3.

The numerical model is based on non-stationary St Venant 2D equations. The initial condition is defined to correspond to a 50 m high wave at the foot of the RBL (analytically, a 32 m wave was calculated). The results of the numerical computation given hereafter show no overtopping of the dam crest.

3. GLOBAL RISK ANALYSIS

Based on the review of the previous reports and additional studies summarized above, the following hazards could threaten the integrity of the Usoy dam or at least modify the seepage regime through it:

- Dam instability
- Internal erosion
- External erosion
- Wave overtopping caused by a landslide

3.1 HAZARD SCENARIOS

3.1.1 DAM INSTABILITY

In static conditions, even for lower bound shear parameters, the stability of the dam is high both for the upstream and the downstream slope.

Under seismic conditions the global stability of the dam remains very high with a factor of safety of more than 4. Local instabilities would have a factor of safety larger than 1.0 for earthquake accelerations<0.4g. For earthquake accelerations >0.4g, according to the empirical relationships given by Newmark [11] and Ambraseys [12], the displacements, that can be generated are likely to be in a range of 0.5 cm - 10 cm. They are regarded as negligible bearing in mind the scale of the dam.

3.1.2 External Erosion

During the last 40 years, the lake level showed a slight tendency to increase. At the current rate, 200 years would be necessary before the lake level reaches the lowest point of the dam crest. Because of the higher permeability of the blocks of the upper part of the dam, it is not possible that the lake level would increase enough to overtop the dam crest. Modification in the seepage regime would be more likely.

Due to the climatic conditions, a sudden increase of the lake level cannot induce an overtopping which could trigger an erosion of the downstream face of the dam. The main phenomenon related to external erosion refers to the evolution of the canyon: this canyon develops presently in soft deposits and does not affect the dam body. Its progression has, in fact, positive effects on the drainage of the dam body.

3.1.3 Internal Erosion

The present seepage process through the dam presents seasonal fluctuations due to the variations of the lake level but remains globally constant over the years. Higher discharges observed exceptionally, when the level of the lake exceeds levels already reached proves the hydrogeological immaturity of the dam. The maturity will be reached as soon as a definitive equilibrium between inflow and outflow is found.

The filtration area extends on a length of about 1000 m along the face of the dam. Its depth is unknown. However, the yearly average fluctuation of the lake level (6,6 m) corresponds to a yearly average fluctuation of the outflow of 20 m^3/s (average minimum and maximum outflow: 37 and 57 m^3/s). This leads to assume that the main part of the filtration occurs in the upper part of the dam (say in the first tenths of meters). Nevertheless, there is no reason to reject the hypothesis of the presence of isolated filtration paths lower down.

Internal erosion and piping processes leading to immediate dangers for the Bartang Valley population are excluded. Nevertheless, the slow modification of the filtration area will go on. Sudden modification of the internal structure of the dam could be induced by earthquakes or waves hitting the dam.

The high number of springs and hydraulic paths make global clogging of the dam very unlikely. Moreover, in case of important clogging of the hydraulic paths, the induced lake level increase would lead water to create new hydraulic paths through the blocks of the upper part of the dam and less impervious layers.

3.1.4 Wave Overtopping

In the present conditions the waves induced by landslides with a volume below 500.10^6 m^3 and a sliding velocity lower than 20 m/s would be lower or slightly over the crest of the dam. The morphology of the lowest part of the dam's crest, made of big blocks with huge crests and pits extending over hundreds of meters, is also unfavourable for run-up. Hence, there is no evidence that a right bank landslide could cause a huge overtopping wave able to threaten the population of the Bartang Valley. In the worst cases analysed, significant volumes of water are trapped in depressions located on the downstream face of the dam. However, their subsequent infiltration through the dam body would modify the seepage regime. Furthermore a wave even not overtopping the dam could nevertheless disturb its internal structure and modify the seepage process through the dam, probably suddenly increasing the discharge downstream of the dam. In any case, the destruction of the dam crest by an overtopping wave is very unlikely. The external erosion processes would also be extremely limited.

3.2 Fault Tree Analysis

The Fault Tree Method of hazard analysis is based on the fact that the threatening event is known and the questions "How can this happen?" and "Are the events sufficient for this to happen?" must be answered. The aim is then to define all the combination of triggering events that will end in the threatening event. Step by step, it is then possible to identify the basic causes that may originate the threatening event. In the present case, the fault tree event is very simple but it gives a good representation of the scenarios that may endanger the people in the Bartang Valley, i.e. a flood with a discharge higher than 400 m^3/s.

3.2 Hazard Analysis

For the hazard and risk analysis of phenomenon difficult to really handle and appreciate, or for which the information is not sufficient to address a definitive statement, it is current practice to organize an Expert Assessment Meeting. During this meeting the hazard scenarios and their probability of occurrence are discussed and one must arrive to a common consensus. An Expert Assessment Meeting has been organized in June 2002 in order to present the main results obtained so far and to analyze together the problem. A tentative analysis of the probability of failure of Usoy dam has been made, starting from the probability of occurrence of the Maximum Credible Earthquake and its subsequent consequences. The paths leading to the highest probability is due to piping failure caused by toe instabilities. These are local instabilities but they could give rise to internal disturbances leading to piping failure, resulting in a sudden increase of the discharge through the dam.

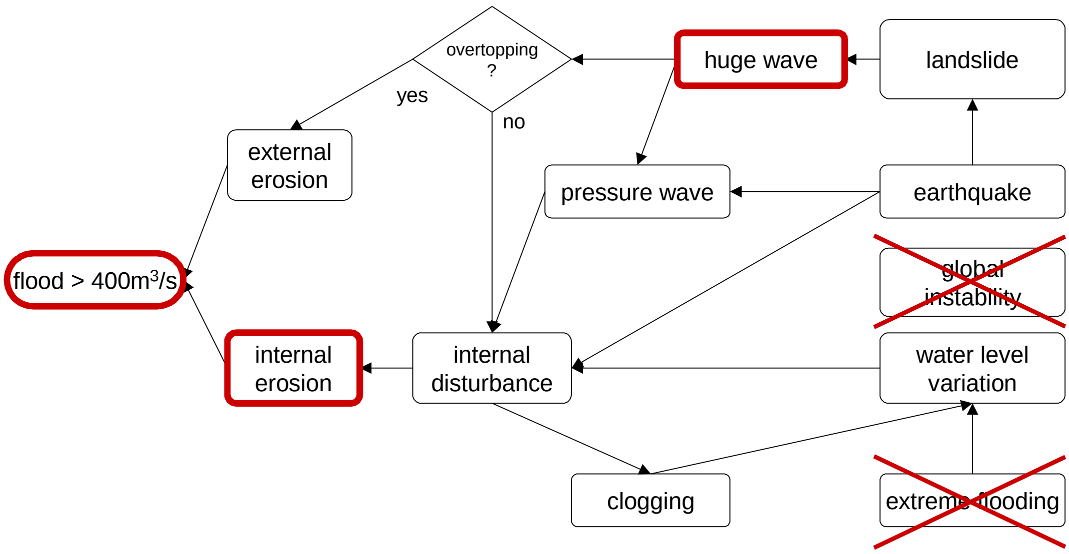

Fig. 7
Fault tree analysis of the Usoy dam safety : major hazards are identified
Arbre des défaillances du barrage d'Usoy . les processus de danger principaux sont mis en évidence

The global probability of occurrence of this event reaches 6.10^{-5} which is comparable to man made dams probability of failure. Therefore, as for other dams, this proves that Sarez has to be subjected to continuous monitoring and that an early warning system has to be installed.

4. MONITORING AND EARLY WARNING SYSTEMS

A Monitoring and Early Warning System (MS & EWS) has been installed in 2004. Components of the Monitoring system are used for triggering alarms and are integrated into the Early Warning system. The Monitoring and Early Warning System comprises mainly the following elements:

- the Monitoring Units (MU) with their own independent power supply
- the Data Acquisition System in the so-called Dam House (CU)
- the Supervisory Control and Data Acquisition System (SCADA) with data collection, front-end, preparation, calculation, storage, analysis and presentation of data in Dushanbe
- the Alert Activating Panels (AAP) for generating manual alerts and the Siren Controllers (SC) for monitoring and activating the sirens

All communications of the data, alarm signals and remote control of the systems are through satellite Inmarsat Mini C system or cables for local short distances. Table 1 presents the equipment of the MU's.

Table 1
Monitored parameters and equipment of the MS &EWS

Monitored parameter	**Comments**
RBL movements	• GPS manual measurement
earthquake	• 3 strong motion accelerographs
lake level	• pressure cell measurement of water level in normal conditions
abnormal wave	• pressure cell used to capture abnormal wave height
dam body movements	• GPS manual measurement
outflow discharge	• automatic radar sensors over the river • flow meter for calibration
flood occurrence	• flood sensors to detect early occurrence of high flows
meteorology	• measurements of basic meteorological parameters at the Dam House

The general layout in Fig. 8 shows the distribution of equipments (MU's) and instruments devoted to MS and EWS.

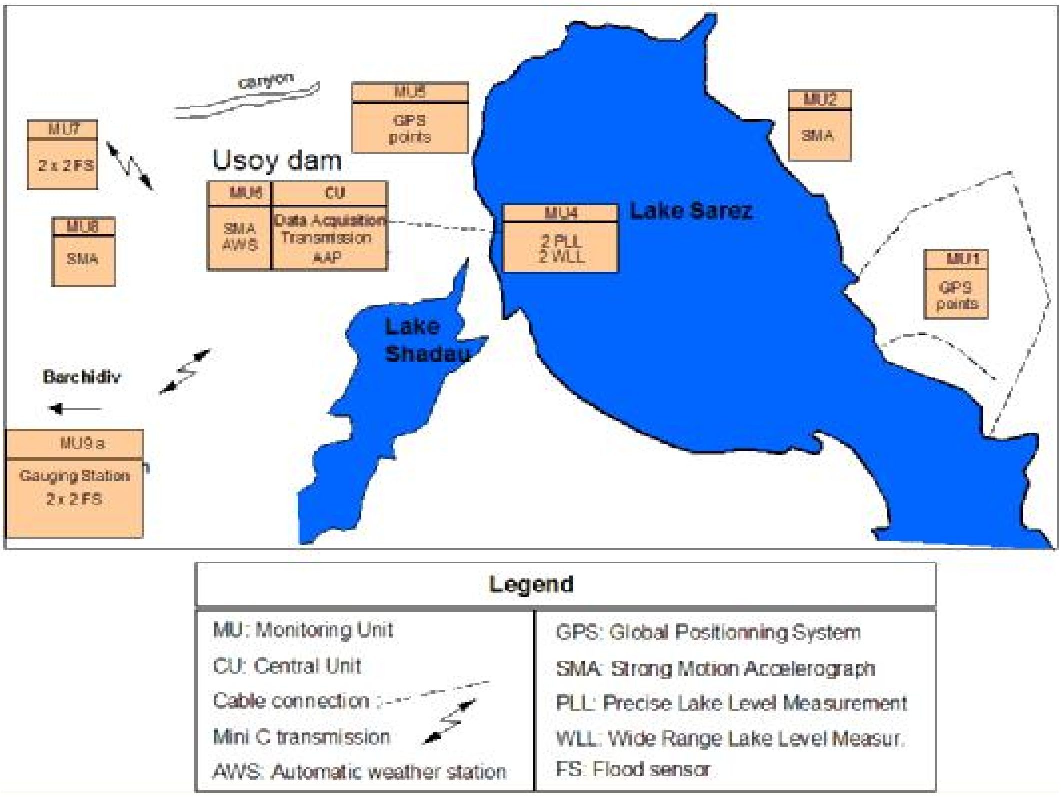

Fig. 8
General layout of MS and EWS instrumentation
Disposition générale de l'instrumentation

Two level of alarms have been defined according to the importance of the phenomenon detected: Alarm Level 1 launches observation or maintenance missions; Alarm Level 2 triggers alarms in 17 villages located downstream. Threshold values have been defined accordingly.

a) b)

Fig. 9

Some elements of the MS & EWS: a) Dam House, weather station ; b) Discharge and flood sensors

Quelques éléments de l'instrumentation: a) Dam House et station météo; b) capteurs de débit et détecteurs de crues

5. CONCLUSIONS

The collection, digitalisation and analysis of much complementary data enabled a better understanding of the behaviour of the Usoy dam and its surroundings. In particular, the present project offered the opportunity to have a synthetic and comprehensive view of the various aspects and phenomena involved.

Under the present conditions, it is clear that a sudden and complete outburst of the Usoy dam is a hypothesis that cannot be reasonably and directly considered. The hazard processes that may modify the present state of the dam and threaten the population living downstream are essentially related to a modification of the internal hydrogeological conditions and, more precisely, the seepage regime. This modification can be the consequence of an earthquake or the pressure and internal perturbations induced by the waves caused by the collapse of the right bank unstable mass. There is no evidence that a right bank collapse could cause a huge overtopping wave able to directly threaten the population of the Bartang Valley. The modification of the seepage regime can result in a sudden increase of the discharge downstream.

The analysis of the hazard scenarios and the risk analysis have provided a valuable basis for the definition and the design of Monitoring and Early Warning systems.

Further works such as boreholes and geophysical investigations would be valuable but they would face rather difficult conditions of implementation. Improvements of the MS and EWS will be decided after a few years of operation. Nevertheless the analysis of the parameters recorded during the first year of operation of the Monitoring system corroborate the results presented here above.

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SUMMARY

Lake Sarez in Tajikistan was formed in 1911 when a massive earthquake-triggered landslide buried the village of Usoy under a 650 m high obstruction which dammed the Murghab River. The resulting 60 km long lake containing over 17 km3 of water is located behind the so-called Usoy natural dam in the Pamir range, the highest dam in the world.

Although the safety of the lake has been studied over many years, significant gaps and inconsistencies existed in the data available. Despite this lack of data, however, it is clear that the risk to the downstream population living in the Bartang and Pianj river valleys is high but had to be quantified.

The article presents the main results of the various studies performed in order to have a better understanding of the phenomena involved and to identify and qualify the hazard processes and assessing the risk related to this particular natural structure. The results are used for the design of Monitoring and Early Warning systems.

Particular attention is devoted to the global static and dynamic analysis of the dam, the hydrological regime, the seepage process through the dam itself as well as the consequences of a large landslide on the right bank sliding into the lake and generating a huge waves

The Monitoring and Early Warning Systems that have been implemented in order to mitigate the risk are briefly presented.

RÉSUMÉ

Le lac Sarez, au Tajikistan, s'est formé en 1911 lorsque qu'un effondrement catastrophique engendré par un séisme a recouvert le village d'Usoy sous une masse de 650m de haut, obstruant la rivière Murghab. Le lac ainsi formé au cœur du massif du Pamir, de 60 km de long, avec un volume de 17 km3, est retenu derrière la digue naturelle d'Usoy qui se trouve être le plus haut barrage au monde.

Bien que les aspects de sécurité du lac aient été étudiés depuis de nombreuses années, plusieurs manques et incohérences entachaient les données à disposition. Cependant, en dépit de l'absence de données complètes, il est clair que le risque menaçant les populations vivant dans les vallées aval de la Bartang et de la Pianj restait élevé et il convenait de le qualifier.

L'article présente les résultats principaux des diverses études entreprises afin d'avoir une meilleure compréhension des phénomènes en jeu et d'identifier et de qualifier les processus de danger et le risque lié à cette structure naturelle particulière. Les résultats ont été utilisé pour la définition et la conception d'un système d'auscultation et d'alarme.

Une attention particulière est dévolue au analyses statiques et dynamiques de la digue, au régimes hydrologiques et hydrogéologiques auxquels elle est soumise ainsi qu'aux conséquences de l'effondrement d'une importante masse rocheuse en rive droite qui en tombant dans le lac pourrait générer des vagues gigantesques.

Les systèmes d'auscultation et d'alarme mis en place afin de réduire le risque lié à Sarez sont également brièvement décrits.