Geohazard monitoring for reservoir and dam safety and sustainability

Surveillance des risques géologiques pour la sûreté et la durabilité des réservoirs et des barrages

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ABSTRACT: In this paper geohazards and their monitoring are considered in the general context of reservoirs and dams. Demonstration is given of a systematic methodology, based on interrelation matrices, to analyze a system of multiple geohazards (multi-hazards) and corresponding monitoring parameters. It is shown how multi-source monitoring can through this methodology be linked to various multi-hazards. Geohazard interrelations are evaluated, as well as monitoring values indicative of different safety levels. The interrelations established have general relevance to reservoirs and dams. This is briefly explained through the case of a large reservoir in Iceland. The methodology constitutes the basis for a comprehensive safety and risk management, which can be used in planning and designing a monitoring program for other infrastructures, and/or a specific geohazards, such as volcano, landslide and more.

RÉSUMÉ : Dans cet article, les géorisques et leur surveillance sont considérés dans le contexte général des réservoirs et des barrages. Une méthodologie systématique, basée sur des matrices d'interrelation pour analyser un système de géorisques multiples et les paramètres de mesure correspondants, est présentée. On démontre comment la surveillance multi source peut, à travers cette méthodologie, être liée à différent types de danger. Les interrelations des géorisques sont évaluées, ainsi que les valeurs de sécurité du système de surveillance. Les interrelations établies ont une importance générale pour les réservoirs et les barrages. Cela est brièvement illustré dans le cas d'un grand réservoir en Islande. La méthodologie présentée constitue la base d'une gestion complète de la sécurité et des risques, et peut être utilisée pour la planification et l'évaluation d'un programme de surveillance d'autres infrastructures et/ou d'un risque géologique spécifique d'origine volcanique ou sismique par exemple.

KEYWORDS: Multi hazards, interrelations, systems theory, multi-source monitoring, geohazards, reservoirs, dams

1 INTRODUCTION

Hazardous events posing threat to reservoirs and dams arise mainly from tectonic, geological as well as hydrological conditions, either local or regional. These hazards are here termed geohazards. Typical examples of geohazards include earthquakes, floods, landslides, volcanism, avalanches and surge waves, such as tsunamis (Lacasse and Nadim, 2008). One geohazard my trigger another and eventually result in catastrophic failure. Reservoirs can also trigger or activate a geohazard, such as reservoir-triggered earthquakes (RTE) and landslides. Monitoring the processes that may lead to hazardous events is one way of preserving safety. Furthermore, a monitoring program aids in assessing the impact of the reservoirs and dams on the environment and in appraising their sustainability.

Geohazards that are generally considered for safety and sustainability of reservoirs and dams are listed in Table 1. For a particular reservoir, the assessment and monitoring of the relevant geohazards is imperative for the planning, design and operation. (Sigtryggsdóttir et al., 2015; Sigtryggsdóttir et al., 2016)

A substantial number of papers exists in the literature, describing monitoring programs for reservoirs and dams that only take into account a limited number of geohazards. The International Commission on Large Dams (ICOLD) has also issued numerous bulletins that either address one or more geohazards briefly for an overall account of the particular subject covered, or they focus on a specific phenomenon related to geohazards. In these bulletins a comprehensive and practical account of each subject is provided with recommendations on monitoring or other actions to be taken. However, neither those or similar bulletins nor journal papers on this subject, give a proper definition of the general concept of what constitutes monitoring of geohazards for reservoirs and dams. This however, is provided by Sigtryggsdóttir et al. (2015), including a detailed account of the geohazards listed in Table 1. Sigtryggsdóttir et al. (2015 and 2016), additionally provide a general classification of the relevant monitoring opportunities.

This paper presents the conceptual model and the systematic approach applied by Sigtryggsdóttir et al (2015 and 2016), along with key results and findings. The methodology is used to link multi-source monitoring to multi-hazards threatening reservoirs and dams for a comprehensive overview of monitoring opportunities and assessment of safety based on values from the monitoring system, and its components. One example of possible application of the conceptual model is given for the case of the Hálslón Reservoir in Iceland

2 METHODOLOGY

The use of a system interrelation matrix is one way of identifying a given hazard interaction from a casual correlation, based on real physical processes. The methodology was originally developed by Hudson (1992) for evaluation of rock systems. Sigtryggsdóttir et al (2015, 2016) extended this method to include multiple systems, each represented with a system interrelation matrix. Interrelations within the respective systems as well as their interrelation to each other, can thereby be investigated.

Constructing an interrelation matrix is a systematic and a fairly straightforward approach. The different processes are aligned diagonally in the interrelation matrix, whereas their possible interrelations are indicated by the off-diagonal cells. The causal relastionship between processes (or parameters) can be traced from each diagonal cell along the row it is in. Each cell represents a causal relationship between the process in the same row as the cell, and the process on the diagonal above or below the cell. Thus, each row contains information on the causal influence/interaction of the process, on the diagonal within that row, on/with all other processes. Conversely, each column contains information on the effects of the other processes on the process on the diagonal within the column.

Interrelation between multiple systems can also be studied in a similar way, as explained by Sigtryggsdóttir et al (2015 and 2016).

The interrelations can be ranked and coded numerically for analysis of causes and effects of each process, as well as dominance and interaction intensity within the system. Five interaction categories are common, using for example numerical values 0,1,2,3,4 to represent respectively, 'none', 'weak', 'medium', 'strong' and 'critical' interrelation (Hudson, 1992). Additionally, color codes can be used and presented in a color coded matrix visually mapping ranked interrelations (Sigtryggsdóttir et al, 2015).

Probability of interrelation is not quantified in the conceptual model presented here, which focuses on providing an overview on the factors affecting the safety of reservoirs and dams in general. However, general probability might be considered vaguely inherent from defining different stages of interrelation as later explained. In the case of a particular reservoir and its dam(s) the probability of different hazards can be assessed and applied to the conceptual model, for example in terms of susceptibility or risk. Example is given on such results in the following.

3 SYSTEMS OF A CONCEPTUAL MODEL

Sigtryggsdóttir et al (2015 and 2016) introduce a conceptual model containing a system of geohazards and a system of associated monitoring opportunites. The systems of the conceptual model is reported in the following along with some of the results from their study. Additionally, an example is given on the application of the model to a particular case of a large reservoir is Iceland, considering susceptibility and risk.

3.1 A *system of geohazards/multihazards and a reservoir*

The assessment of multi-hazards is important for reservoir and dam safety, considering that failure of a reservoir or damage to a dam and appurtenant structures may result from a geohazard triggering another geohazard. Moreover, individual geohazards can be triggered (induced) by both natural processes and human-induced changes in the environment. The natural triggering processes can include climatic processes, such as precipitation, temperature and wind, whereas, the impounding of a reservoir is an example of human-induced change. Examples of reservoir-induced geohazards include: reservoir triggered earthquakes (RTE) (Gupta, 2002; ICOLD, 2011) and landslides (Schuster, 1979; Nonveiller, 1987). Thus, a reservoir's potential to induce or trigger different geohazards has to be considered during both its impounding and operation.

Figure 1 describes a system of reservoir and geohazard interrelations in a color-coded matrix. The construction of this matrix is based on an extensive literature study presented by Sigtryggsdóttir et al., (2015 and 2016), along with a detailed account on reservoir and geohazard interaction and interrelations. The color codes of the interrelations can be given a numerical value in further analysis. The interrelation matrix can then be depicted as in Figure 2. For a specific project the interrelations can further be defined based on either risk or susceptibility (Sigtryggsdóttir et al., 2016).

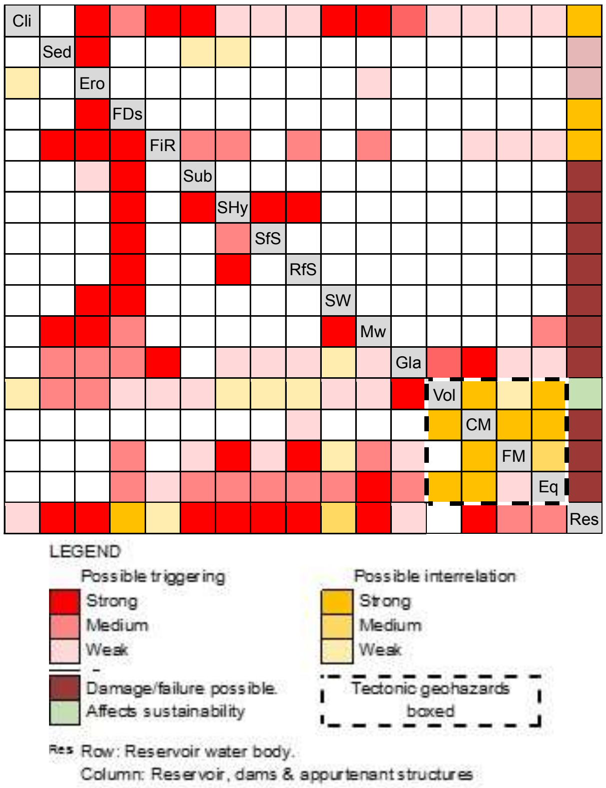

Figure 1. Matrix of reservoir and geohazards interaction and interrelation. (Sigtryggsdóttir et al., 2015). The diagonal represents the following processes (alphabetic order): Cli-Climate; CM-Crustal Movements; Ero-Surface erosion and scouring; Eq-Earthquake; FDs-Flooding out of the reservoir (downstream); FiR-Flooding into reservoir; FM-Fault movement in reservoir/dam foundation; Gla-Glacial; Res (row)-Reservoir water body and elevation; Res(column)-Reservoir, dams and appurtenant structures; Rfs-Rock foundation stability; Sed-Sedimentation; SfS-Soil foundation stability; SHy-Subsurface hydraulics; Sub-Subsidence; SW-Surge wave on reservoir; Vol-Volcanism.

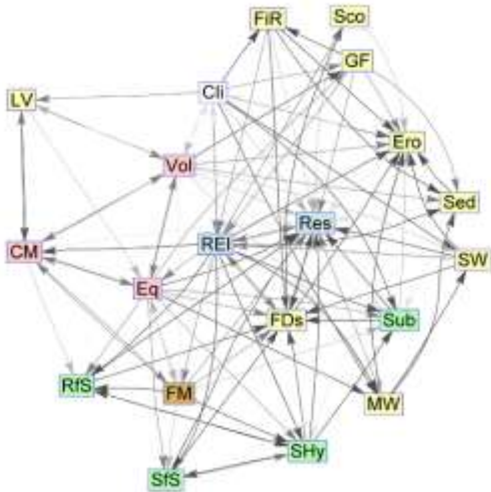

Figure 2. Interrelations between within the reservoir/geohazard system (Sigtryggsdóttir et al., 2016) with numerical values for the interrelations presented in Figure 1. The arrowhead of the connecting lines points to the affected component. The different shades of grey of the connecting lines represent strength of interrelation, the darkest shade for the strongest interrelation/triggering.

The potential for a reservoir to induce geohazards, such as reservoir-triggered earthquakes increases with increased storage level and larger oscillations of the reservoir elevation (ICOLD, 2011). Thus, for a particular reservoir the potential of some of the interrelations described in the figure depends on the actual tectonic state of the reservoir region, climate conditions, geological setting as well as the size of the reservoir.

3.2 A *system representing monitoring of multi-hazards*

In general, the monitoring network and related instruments should be selected and located either to assist in providing an answer to a specific question related to operation, safety and risk reduction, or to monitor any changes in the environment indicating that a geohazard might develop into a damaging or catastrophic event. The aim of a geohazard monitoring for reservoirs and dams is to detect precursors when the significance of the information presented by the monitoring data can be realized and its message acted upon with appropriate mitigating measures.

Table 1. Geohazards to consider in general for safety and sustainability of reservoirs and dams. (Sigtryggsdóttir et al., 2015 and 2016).

Regional	Local (large reservoir area)	Site specific (in the foundation)
Tectonic	**Surficial**	**Dam/reservoir**
Earthquakes and faulting	Flooding into the reservoir	Subsurface hydraulics [h)]
Crustal movements	Flooding out of the reservoir	Movement on faults & lineaments
Volcanism [a)]	Mass wasting into reservoir [c)]	Rock foundation stability [i)]
Surficial	Surge wave on reservoir	Soil foundation stability [j)]
Glaciers	Surface erosion [d)]	Subsidence/differential settlements [f-g)]
Glacial outburst floods [b)]	Scouring [e)]	
Surface load variations	Sedimentation in the reservoir	
	Land subsidence [f)]	

a) Eruptions, magma movement and magma/dyke intrusion.
b) Due to volcanic eruption or outburst of a glacial lake.
c) Landslides, rock slide/creep, rock fall, debris flow/lahars, avalanches, ice calving, glacial surge
d) Reservoir bank erosion, erosion in the larger reservoir area, downstream river bank erosion,
e) Erosion and scouring of unlined rock at water outlets from the reservoir
f) Soluble rock, liquefaction, compressible, collapsing/shrinking soils, permafrost, subsurface erosion/piping
g) Dispersive soils, non-uniform foundation conditions causing differential settlement.
h) Subsurface erosion and piping, dissolution, multi-aquifer
i) Rock block/fault movements, downstream dipping rock beds, uplift pressure, and subsurface hydraulics.
j) Liquefaction, highly plastic stiff clays, stability of abutment slopes, subsurface erosion and piping.

Standard monitoring of reservoirs and dams provides results that can possibly indicate changes relating to geohazards. These changes include: seepage/leakage/turbidity, pore pressure and groundwater measurements, flow measurements in rivers, reservoir elevation and any meteorological quantities (temperature, precipitation, wind speed). Additionally, individual instruments or a monitoring network should be installed to monitor a specific geohazard of relevance to the project, such as pre-existing landslides, rock slopes or other types of mass wasting in the reservoir area, foundation deformations, glacial hazards, crustal movements and movements on faults and lineaments, micro-seismicity as well as strong earthquake motion. Visual observations of relevant features (leakage, seepage, crack development and deformation processes) in regular site visits should also be a part of the monitoring program for geohazards. The parameters constituting monitoring of geohazards for reservoirs and dams as defined by Sigtryggsdóttir et al (2015 and 2016) are listed in Table 2. These represent the monitoring system parameters.

The interrelation between monitoring parameters can be studied in an interrelation matrix similar to the one for multi-hazards in Figure 1, with the processes in Table 2 on the diagonal (Sigtryggsdóttir et al, 2015 and 2016). Such study can aid in identifying precursory signals within the monitoring system

3.3 *Multi-hazards linked to multi-source monitoring*

The multi-hazard can be linked to the multi-source monitoring in several ways considering the two system introduced, i.e. the one of geohazards, and the other of the relevant monitoring possibilities. One connection between the two is through an investigation of the potential effect or possibilities that individual geohazards will affect or trigger monitoring within the monitoring system, as explained by Sigtryggsdóttir et al (2016). Another connection is to define the alarm and/or back-calculation potential of individual monitoring parameters, as shown in Figure 3. In Figure 3 the greenish colors describe the alarm potential, and the letter B in a cell indicates whether these can be used in back-calculation procedures or evaluation of the respective geohazard. The “Monitoring/Strong alarm” color code states that the instrumentation is directly monitoring the specified geohazard. While “Medium” and “Weak” green cell color, states that the monitoring data might contain warning or alarm for an impending geohazard.

Table 2. Monitoring of geohazards for reservoirs and dams.

Parameter	Monitoring
Reservoir elevation	Monitoring reservoir elevation. Temperature.
Groundwater	Monitoring groundwater level. Temperature and chemical measurements at selected boreholes.
Leakage/Turbidity	Leakage/seepage quantity. Suspended soils. Temperature of springs and seeping groundwater.
Fault movements	Monitoring: Movement on faults and lineaments in the dam/reservoir foundation.
Crustal Movements	Geodetic methods/remote sensing monitoring crustal movement/surface load variations.
Microseismicity	Network of seismometers for monitoring microseismicity and strong earthquakes.
Strong earthquake	Accelerometers on dams/appurtenant structures/foundation monitoring earthquakes.
Flow measurements	Monitoring flow in rivers both upstream and in the dammed river basin downstream.
Meteorological data	Monitoring climate: temperature, precipitation and wind. Air quality.
Pore pressure	Piezometers, temperature measurements, observation wells.
Specific process	Sensory system/geodetic methods/remote sensing/field surveys to monitor, as may apply: Subsidence, soil foundation, rock foundation, mass wasting, sedimentation, erosion, scouring, glacial lake, etc.

The interrelations in Figure 3 can also be coded numerically for further investigation of the monitoring value of individual monitoring parameters for the geohazard system, or their suitability of the monitoring system to monitor individual geohazard. Results from such analysis of the conceptual model are provided in: Figure 4, for the value of the whole monitoring system to monitor individual hazards; and Figure 5, for the monitoring value of the different monitoring parameters.

In Figure 6, the conceptual model has been used to evaluate instrumentation and monitoring networks installed for the

Hálslón Reservoir in Iceland. Susceptibility and risk indexes were defined for the geohazards posing threat to the project and applied to the conceptual model. The procedure is described by Sigtryggsdóttir et al (2016). The result for the monitoring value of the different monitoring parameters are presented in Figure 6, from both a susceptibility and a risk perspective.

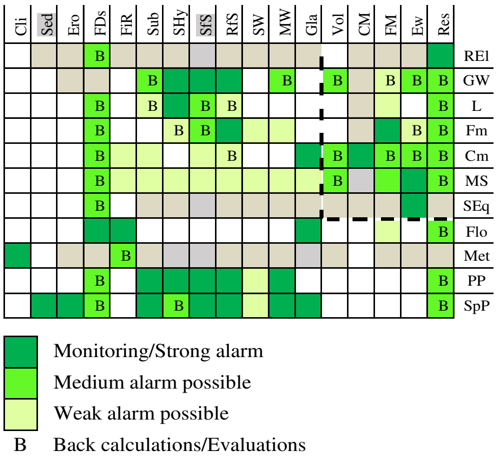

Figure 3. Interrelations between the multi-hazard processes in Fig. 1 and the monitoring parameters in Fig 2. The matrix represents the possibilities for warning signal detection in the monitoring parameters. (Sigtryggsdóttir et al., 2015). The monitoring parameters are: Cm-Crustal movement monitoring; Flo-Flow measurements; Fm-Fault movement monitoring; GW-Groundwater; L-Leakage/Seepage/Turbidity; Met-Meteorological data; MS-Micro seismicity; PP-Pore pressure; REl-Reservoir elevation; Sp-Specific Process Monitoring; SEq-Strong EQ Motion.

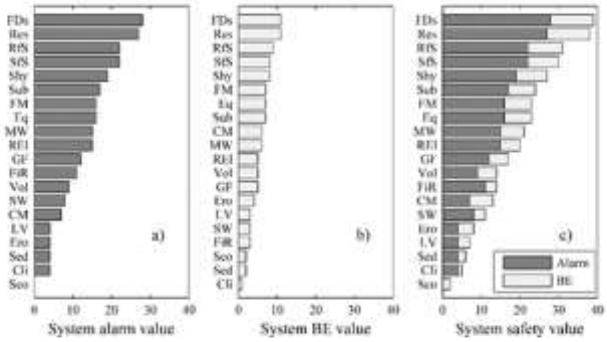

Figure 4. The monitoring system value for individual components of the multi-hazard system. a) System alarm value. b) System BE value, epresenting the number of monitoring components within the SafeMon system for back-calculation and evaluation of individual hazards.
c) Collective system safety value (Sigtryggsdóttir et al., 2016).

4 FINAL REMARKS

The purpose of this study is to demonstrate the importance of considering interrelation and interaction of geohazards related to monitoring of reservoirs and dams and the possibilities associated with the methodology presented.

The methodology reported upon can be applied to any infrastructure or physical elements. This lays the foundation, first, for a comprehensive multi-hazard assessment and, second, for a systematic approach to planning and implementing safety monitoring. The interrelations established through such analysis can be easily adopted and modified to fit different settings. Consequently, this systematic methodology can be applied to investigate multiple systems, identify precursors as well as pathways and constitute a comprehensive safety and risk management aiming at enhancing the mitigation of risk.

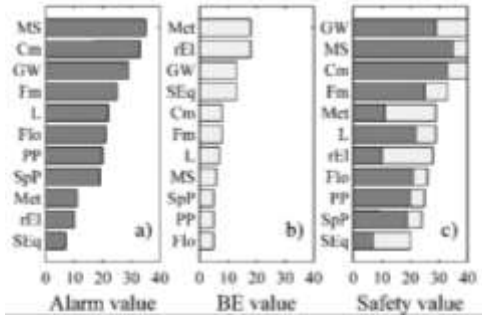

Figure 5. Value of the monitoring components for monitoring processes within the multi-hazard system. a) Alarm value. b) Value for back-calculations and evaluation (BE value). c) Safety value.

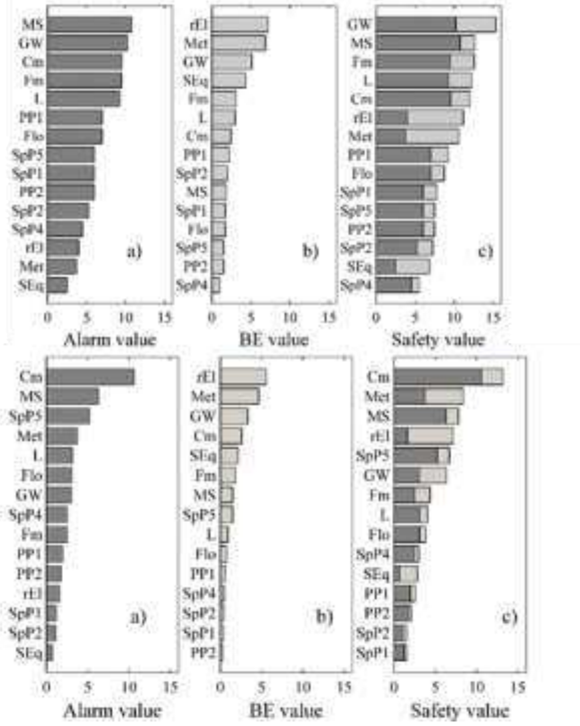

Figure 6. Monitoring values of the case study's monitoring components based on one a risk perspective (above) and susceptibility (below). (Sigtryggsdóttir et al., 2016).

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