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NATURAL DAMS IN ARMENIA: LANDSLIDE HAZARD AND RISK ASSESSMENT

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Armenia lies in the central part of the Armenian Highland that has a high-energy relief, which, under the conditions of high seismicity, determines development of large-scale rockslides and landslides.

Armenian historical chronicles record many cases of major earthquake-induced rockslides forming large retaining water bodies, and numerous smaller ones (Table 1).

The use of GIS-format databases on historical chronicles, remote sensing, field study results and geotechnical investigation helps to obtain important information related to formation of natural rockslide dams, the way their man-made component is operated today, and to assess natural and man-made components of the landslide hazard and risk.

There are more than 2000 large landslides in the territory of Armenia. In the recent years, activation of landslides forced total or partial evacuation of 5 populated areas, left homeless about 2000 families, caused casualties and loss of agricultural lands. The landslide hazard threatens transport, mining and energy facilities, including water reservoirs. About 25% of the total number of natural and man-made water reservoirs fall within landslide hazard zones.

Analysis of the databases allows us to identify a group of problems related to formation, operation, and rates of landslide hazard for natural dams in Armenia.

Natural rockslide dams created numerous, but small-volume water bodies in proximal depressions of large landslides caused by strong pre-historical and historical earthquakes (Table 1). Located close to each other, many of them have been linked by numerous man-made canals and used for irrigation since the ancient times. Such system presents a good example of how people succeeded in careful and thoughtful use of the hazardous natural process for their benefit.

The majority of small rockslide dams in Armenia have the fol-

Table 1 - Historical data on landslide-dammed lakes in Armenia

Earthquake Date and Magnitude	Location	Description of rockslide dams and water bodies
735 21.06. 7.1	Vaik and Sunik Provinces, Republic of Armenia.	Large rockslides in the region of the Sissian Pass and many minor ones; a large water body in the region of the Sissian Pass, broken today; many small water bodies in the Vaik and Sunik Provinces that are presently used as water reservoirs.
800-802 6.9	Kogatu Mountains, western Armenian Highland, corresponding to the today's region of the city of Kamakh in Eastern Turkey.	A large rockslide that dammed the Euphrates River for 1 day.
1139 30.09. 7.5	Region of the city of Ganzak (Gyanja), Azerbaijan	Mount Algarak (Kyapaz) collapsed down into the river and formed Lake Geighel, preserving till today.
1482 7.5	Kogatu Mountains	The rockslide dammed the Euphrates River and flooded the valley of the city of Yerznka (Erzinjan)
1648 7.0	Lake Van region	Numerous rockslides formed small water bodies
1669 01. 04. 6.5	Lake Van region	A large rockslide near the city of Varag formed a river dam that has preserved till today.
1679 14. 06. 6.9	The Kotayk Province, an area not far from the Yerevan City	Numerous medium-size and small rockslides formed small water bodies in the Kotayk Province.
1840 02. 07. 7.4	The Ararat Valley	A rockslide from Mount Ararat dammed the Akory Canyon. Few days later the dam was broken through. Many rockslides created dams in the Arax River and in other rivers. Some of those small water bodies have preserved and are in use till today.

lowing general features:

- The dams are created by earthquake-induced rockslides and are located within the limits of large landslide bodies displaying diverse rates of recent activity.
- The water reservoirs have been used for irrigation since the ancient and medieval periods and are in use even presently.
- During the last 30 to 40 years, many of natural rockslide dams underwent reconstruction to enlarge their height or length with the purpose of increase volumes of irrigation water.
- These works were conducted by means of excavation of soils from landslide areas nearby, which, as a rule, led to landslide destabilisation and activation of landslide phenomena.
- As a rule, physical and mechanical properties of soils in the overbuilt part of such dam are worse than in its natural, rockslide component.
- In most of the cases, increased height of a dam and larger volume of the water reservoir determined higher rate and amplitude of erosion processes on the landslide, percolation of water from beneath of the man-made part of the dam, and, as result, additional destabilisation of the entire landslide.

All of the dams fall within areas of high seismic hazard estimated at acceleration values of 0.3g–0.5g (exceedance probability of 10% in 500 years). In the meantime, when assessing seismic hazard for a dam, it is seldom taken into account that landslide slope would become unstable even at much lower acceleration values.

All these factors create serious man-made hazard for the traditional irrigation system developed since the ancient and based on use of small rockslide-dammed water bodies, time, and, therefore, increase the level of natural risk for many settlements located in their neighborhood.

Two typical examples could illustrate this.

The reservoir of Bartsrouni falls within a landslide located in the Vaiyots-dzor Province. This landslide has been characterised by high rate of recent activity. Activity indicators are recorded in the central and proximal parts of the landslide only, i.e., in the area of the reservoir. Villagers used this small reservoir even in the ancient time. In 1971, the reservoir was deepened, while the length and the height of its dam were increased up to 125 m and 13 m, respectively. As a result, the volume of water in the reservoir increased up to 92000 m^3, which led to drastic activation of landslide processes and rapid destruction of the dam. The situation required reconstruction works, which were accomplished in 1988. If this reservoir is considered as an artificial structure, one can describe its present-day condition as critical and capable of leading to complete destruction and dam breach in near future. The distance of transit along the watercourse bed to the village of Bartsrouni is 2 km. Now, there is a discussion concerning possible total demolition of the reservoir in view of the landslide hazard. However, this decision, if taken and implemented, would threaten the agricultural economy in the village of Bartsrouni and well-being of its population.

The water reservoir of Hors is situated on the primary landslide terrace of an earthquake-triggered landslide also located in the Vaiyots-dzor area. Several strong historical earthquakes recorded at this area occurred in 735, 906 and 1679 A.D.. Several more minor water bodies are located nearby the Hors reservoir. All of them have been formed as a result of earthquake-induced landslide activation and have been used for irrigation at least since as early as the 9^{th} –10^{th} centuries A.D.. The Garni active fault (M_{max}=7.1) and the Salvart active fault (M_{max}=7.0) are the main structures responsible for the high seismic hazard rate at the water reservoir site. The dam of the Hors reservoir is 6 m high, and its length along the crest is 178 m. Its height has been artificially increased during the last years. Quality of fill-up soil in the heightened part of the dam is inadequate, while increased volume of the water reservoir has caused activation of erosion processes and facilitated rapid wash-out in the upper part of the dam. As a consequence, the use of the water reservoir for irrigation was stopped. Showing no signs of activity, the landslide where the water reservoir is located can be easily destabilised under a seismic impact. With consideration of ground conditions, expected peak horizontal accelerations are estimated at 0.46g at the dam's basement, and our calculations by Geoslope software indicate that the dam will lose stability at an acceleration value of 0.3g. The distance of transit along the watercourse bed to the village of Hors will comprise 2.5 km.