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Karl Terzaghi and karst in Croatia 110 years ago

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Experience with some investigation and remediation methods in evaporite karst

Iskustva nekih istraživanja i metoda remedijacije u evaporitnom kršu

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Abstract

The understanding of properties of evaporite karst nature is complex geotechnical task. For the evaluation of karstified rock mass properties, systematic, complex, and usually long investigations are needed. The crucial starting point for any dam design, particularly in evaporites is good geological concept based on precise geological map. Due to complex genetic diversity of evaporite rocks the required investigation approaches have some specifities. The fast karstification process as consequence of fast dissolution generates substantial seepage, sometime failures, in the case of number of dams and reservoirs in evaporites. Dynamic of karstification and destructive processes in evaporites is much faster than in carbonate rocks. To deal with this kind of hazards the complex investigations should be applied. Prevention and remediation of large structures in evaporites is much more complex than in karstified carbonate rocks. Experiance with development and application of different chemical components for grouting in evaporites is presented.

Keywords: evaporites, karst, dams, reservoirs, oxaloaluminosilicate, grout curtain

Sažetak

Razumijevanje svojstava prirode evaporitnog krša složen je geotehnički zadatak. Za procjenu svojstava karstificiranih stijenskih masa potrebne su sustavne, složene i obično dugotrajna istraživanja. Ključno polazište za bilo koju konstrukciju brane, osobito u vaporitima, je dobar geološki koncept koji se temelji na preciznoj geološkoj karti. Zbog složene genetske raznolikosti evaporitnih stijena, potrebni istraživački pristupi imaju neke specifičnosti. Brzi proces okršavanja kao posljedica brzog otapanja stvara značajnaprocijeđivanja , ponekad i slomove, kod mnogih brana i akumulacija u evaporitima. Dinamika karstifikacije i destruktivnih procesa u evaporitimaje mnogo brža nego u karbonatnim stijenama. Kako bi se nosili s ovom vrstom hazarda potrebno je primijeniti složena istraživanja. Prevencija i sanacija velikih konstrukcija u evaporitima mnogo je složenija nego u karstificiranim karbonatnim stijenama. Prikazano je iskustvo s razvojem i primjenom različitih kemijskih komponenti za injektiranje u evaporitima.

Ključne riječi: evaporiti, krš, brane, akumulacije, oksaloaluminosilikat, injekcijska zavjesa

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Introduction

Evaporite rocks are widespread all over the world and underlay about 25% of the global continental surface. Klimchouk et al. (1996) listed more than 35 countries and regions with recorded outcrops of gypsum. Halide rocks are widespread also. In areas of the former USSR salt deposits cover more than 2.3 million km² (Korotkevich 1970). The extent of sulphate rocks either at the surface or at depth beneath it is great: Ford & Williams (2007) estimated that gypsum/anhydrite and/or salt deposits underlie 25% of the continental surface (approx. 60 million km²), while Maksimovich (1962) calculated that the area of the continents underlain by gypsum/anhydrite alone is about 7 million km². A number of dams and reservoirs constructed in soluble evaporite rocks all over the world have been affected by dissolution. From beginning of the 20th Century more than sixty dams have been affected by gypsum and salt dissolution problems. Some of the dams failed to retain water up to their design levels due to extensive leakage, some of them collapsed catastrophically, some others were abandoned, and some reservoirs suffer due to severe solute pollution of the stored water. Numerous dams in evaporites, mostly in gypsum, need expensive rehabilitation. Due to the complex genetic diversity found in evaporite rocks, the investigative approaches must be specific. First of all, the role of chemistry and hydrochemistry is very important because of the high and rapid solubility of these rocks.

Because of the nature of evaporites, in many cases the problem has often been too complicated for the sealing technology available. Despite extensive investigation programs and long-lasting attempts at sealing treatments, the problems with some dams could not be overcome.

Properties of evaporites

The most common evaporite rocks encountered at dam sites and reservoir areas are the calcium sulphate minerals, gypsum and anhydrite, and salt, the principal chloride (halite) mineral.

Based on a number of different geomorphological and hydrogeological factors Klimchouk and Ford (2000) distinguish 7 common evaporite karst types: Syngenetic; Intrastratal; Deep-seated; Subjacent; Entrenched; Open and Denuded and Mantled Evaporite Karst.

Gypsum and anhydrite have significant viscosity. Fracturing in them is rough to brittle, often grainy. Gypsum karst develops more rapidly than carbonate karst. Its distribution is not limited either by temperature (in the range from 0 °C to 40 °C) nor by the composition of natural waters. Gypsum karst is characterized by collapses, whose frequency can exceed 2 per km² per year, and a high density of sinkholes (up to 1000 per km²), Gorbunova (1977).

Rock salt (halite) is sodium chloride (NaCl). Salt is incompressible, mechanically weak and flows like a fluid or plastic. Salt will move only if the driving forces exceed the resistance to flow (Hudec and Jackson, 2007). Rock salt is about 1000 times more soluble than limestone and 180 times more soluble than gypsum (Ford and Williams, 2007). The change in the solubility of NaCl with a change in temperature is insignificant; over the range from 0 to 100ºC it only increases by 10%. However, this change, 360 g/L H2O, is huge when compared to the total solubility of the other karst rocks, for example - carbonates (0.055 g/L).

Once the solution process in evaporites begins, seepage flow paths will enlarge, forming conduits and other voids, the piping of any unconsolidated sediments trapped in paleokarst features may increase tremendously and, alone or together, lead to failure. These processes are provoked by the unnaturally rapid and drastic changes in the hydrostatic and hydrodynamic conditions that will prevail within the evaporite rock mass as the water level rises behind the dam, including very large increases of pressure, change of laminar flows to turbulent flows, and substantial increases in the dissolution capacity. As a consequence of these processes the geotechnical stability in geological formations containing evaporites is likely to be drastically reduced; the bearing capacity becomes weaker, grout curtains become perforated by solution channels, reservoir slopes become unstable and the water becomes polluted with high concentrations of sulphates and, perhaps, salt.

The ultimate consequence of all these processes, almost always mutually coupled, is leakage from the reservoir, induced collapses, creation of landslides and, sometimes, the catastrophic failure of the dam and water pollution. In many cases leakage is coupled with karst collapses in the reservoir floor, the dam site and in the vicinity of the reservoir.

Geohazards associated with dams and reservoirs in evaporites

Evaporites are extremely vulnerable geological formations for construction of any large structure, particularly for dams and reservoirs. During the operation of dams and reservoirs in karstified evaporite rocks a number of different destructive processes may endanger their integrity. The most common and important are the following.

Seepage/leakage from the reservoir: Mosul Reservoir (Iraq), 1400 L/s (Guzina et al., 1991); Joumina Reservoir (Tunisia) to about 1.0 m^3/s (Sari, 2013); Huoshipo Reservoir (China) reaches 237 L/s (Lu and Cooper, 1997); Quail Creek Dike (USA) seepage exceeding 0.340 m^3/s in 2002 (Payton and Hansen, 2003); Anchor Reservoir (USA) totally dried up (Jarvis, 2003); McMillan Reservoir (USA) from 0.28 m^3/s to 2.8 m^3/s (Cox, 1967); Caspe Dam site (Spain) to 200 L/s (Mancebo Piqueres et al., 2014); Alloz Dam (Spain) the increasing dissolution and leakage required costly remedial works (Gutierrez et al., 2003); Kangir Reservoir (Iran) up to 650 L/s (Rezaei et al., 2017); Mujib Dam (Jordan) seepage springs appeared in the right bank.

Instability in the dam foundations: St. Francis Dam (USA); Quail Creek Dike (USA); San Juan earth dam (Spain) (Gutierrez et al., 2003); The stability of the foundations of the Mosul Dam in Iraq has recently become of major concern to the world (Adamo et al., 2015).

Induced collapses and/or subsidences: Kama Reservoir (Russia); Bratsk Reservoir (Russia); Mosul Dam; Anchor Dam (USA); Upper Mangum Dam (USA) (Johnson, 2003); Gotvand Reservoir (Iran) (Milanović, 2004); Quail Creek Reservoir (USA); Houshipo Reservoir (China) (Wuzhou, 1988); La Loteta Dam (Spain) (Gutierrez et al., 2015); Toktogul Dam (Kyrgyzstan, salt).

Instability of the reservoir slopes (above and below the waterline): St. Francis Dam (USA, 1928); Kama Reservoir (Russia); Gotvand Reservoir (Iran).

Pollution of the reservoir water: A number of reservoirs in evaporites, mostly in Iran, are exposed to pollution due to contact with evaporite rocks: Gotvand, 15 Khordad, Marun, Jarreh, Seymareh, Kowsar, Nargesi, Khersan III, Kangir, and probably more.

Investigations of evaporites

Understanding the properties of natural evaporite karst is a complex task. The major hydrogeological and geotechnical properties that define karst very often change from place-to-place, both quantitatively and qualitatively. The crucial starting point for any dam design, particularly in evaporites, is a good geological conceptual understanding that is based comprehensive investigations at the site and in its environs. In general, the basic methods regularly applied in geologic and hydrogeologic practice are the first step in what will be a complex and phased approach: geological mapping, application of remote sensing methods, geologic structural analysis, geomorphological analyses, location and identification of all karstic features, hydrological measurements and monitoring, tracer tests, drilling of investigation boreholes, monitoring of water tables with piezometers, geodetic monitoring, hydrochemical investigations and geophysical methods.

Due to the rapid destruction that can occur in evaporites, substantial (and often abrupt) changes in the surface topography are frequent. One of basic diagnostic features is the sinkhole, ranging from initial, almost unnoticeable sagging up to deep sinkholes, recently created or known as historical events (paleo-sinkholes). Registration of these forms during the investigation stage, at the dam site or reservoir area, indicates possible seepage problems and the potential vulnerability of the structure. Opening of new sinkholes during the operation of a reservoir implies a very serious problem and possible failure. Reports from existing engineering practice show that new sinkholes are frequently registered in the bottoms and banks during operation of number of dams and reservoirs in evaporites.

The key objective of investigation is to confirm the feasibility of building a dam and reservoir when evaporites are present. After detailed investigations some dam sites have been abandoned (e.g. Cedar Ridge and Mangum dam sites, USA), while others have had to be comprehensively re-designed (e.g. the bottom outlet at Gotvand Dam, Iran).

Hydrochemical investigations are a powerful tool which enables characterization of numerous processes in areas of great hydrogeological complexity such as evaporites with karst. To estimate dissolution rates during reservoir operations a number of different tests on site, in the laboratory and with scale models were used during the investigation phases in a number of dams in evaporites: Kama Dam (Russia); Rogun Dam and the site of the Lower Kafirnigan Dam (Tajikistan); Mosul (Iraq); Gotvand Reservoir (Iran); Caspe Dam, (Spain), among the others.

Geophysical investigations are frequently applied in evaporites. Based on experience with the wide spectrum of geophysical methods applied by different authors, Ezersky et al (2017) recommend application of Surface Nuclear Magnetic Resonance (3D-SNMR) for locating water-filled caverns and estimating their volume; evaluation of groundwater aggressiveness using Electromagnetics (TEM); the seismic refraction (SRFR) and Multichannel analysis of surface waves (MASW) methods for salt layer mapping and evaluation of its karstification.

Particularly comprehensive were investigations and analysis of the geotechnical properties of the grout mix for grouting curtain construction in gypsiferous rock at the Kama Dam foundation, Maksimovich (2006). To obtain an idea of the total number of components of the liquid phase of the gel that can go into solution and the nature of gelation as the solution moves along the surface of the gel, the special laboratory device was constructed. Chemical interaction of the natural environment with materials injected into the rock, as well as the types of mass transfer in the massif is important to improve the systems that affecting the filtration properties of rocks. Such systems include injection solution - groundwater, gel - groundwater, gypsum - post-injection solutions, gel - gypsum. The mechanism of physic-chemical nature and direction of the processes in the selected systems were investigated. The calculation of filtration coefficients by means of mathematical modeling showed that prior to the injection, an increase in the permeability of cement based grout curtain and gypsum rocks occurred by time. After the curtain was consolidated, its filtration coefficient decreased 2.5 times in upper section (sandy-clayey sediments close to the dam foundation) and almost 100 times in the section of Upper Solikamsk formation. For 4 years after the completion of injection work in the Upper Solikamsk horizon, which is characterized by a high content of gypsum, the filtration coefficient of the curtain and the 5 m zone behind it has decreased by 2 times. Such a decrease in permeability occurs due to plugging of residual cracks in the body of the curtain and beyond its borders due to the post-injection processes considered.

Prevention and Remediation

Prevention and remediation of public structures in evaporites is much more complex than in karstified carbonate rocks. Much lower mechanical strength and much higher solubility when in contact with water (particularly if it is flowing or under pressure) determines that these rocks are dubious and hazardous foundations for dams. However, evaporites that are merely precipitated fillings in joints in stronger rocks, or in the form of laminations or thin beds between thicker limestone beds and silt/clay deposits are sometimes considered to acceptable foundations for dam construction. In the past the conventional geotechnical preventive structures were usually applied in such conditions, on the surface - geotextile or other blankets, aprons, sinkhole fillings, etc; and underground - grout curtains, cut-off walls, plugging cavities and other voids. In many cases both surface and underground preventives were applied. After the first problems and failures occurred some dams were abandoned, or the conventional geotechnical prevention methods were improved and adapted to the distinctive properties of evaporites. To solve the crucial problem of dangerously high solubility, investigations were focused on finding new grout mixes and new chemicals to eliminate or mitigate the dissolution.

Plugging solution caverns found close below the foundation of the dam and construction of grout curtain in rocks containing evaporites is challenging task. Particularly is problematic application of cement based grout mix. At some cases results are positive (Hessigheim structure, Wittke and Hermening, 1996), however at many cases results are questionable.

In the case of grout curtain at the Kama Dam foundation the gypsiferous rocks were grouted with gel-forming thin solutions with viscosity close to water. So thin slurry can penetrates into the narrow joints. One such solution is oxaloaluminosilicate developed in Laboratory of Geology Department, MSU. The solution was applied for additional improvement (consolidation) of grout curtain constructed in fractured gypsiferous rocks. The grout mix consists of two components: sodium silicate with a density of 1.19 g/cm^3 and hardener. The complex hardener is an aqueous solution of aluminium sulphate and oxalic acid. As result of using the oxaloalumosilicate solution the specific seepage through the curtain does not exceed 0.005 L/min. Experience and results of further investigations suggests that these solutions could be used as additives to clay, clay-cement and cement grouts when stabilising gypsiferous rocks (Maksimovich, 2006).

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