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Dams and Reservoirs in Evaporites

Springer

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Foreword

The relationship of the Milanovic and LaMoreaux families goes back many years through Petar and my father, Dr. Phil LaMoreaux, and today through Petar's son Sasa's family and mine. Throughout this time, we have shared many activities both professional and personal, so it was a special honor when Petar asked me to write a forward for his new book.

Dams and reservoirs in evaporites are certainly an excellent culmination of Petar's investigations into carbonate and evaporite terrains and worthy of the wide readership which we are pleased to be able to offer through Springer's worldwide marketing and distribution network. This is one of many Springer publications that I and my father have worked with Petar on over the years.

In PE LaMoreaux & Associates, Inc. (PELA) library, we have a signed copy of Petar's book Karst Hydrogeology published in 1981. Petar gave it to Dr. LaMoreaux when he and his family came to Alabama in the 1980s and used our family's home as the base for their trip throughout the US national parks and US geological survey and state geological survey offices around the country.

Petar, Dr. LaMoreaux, Sasa, and I have served on and continue to serve as members of the International Association of Hydrogeologists (IAH) Karst Commission which has been and continues to be a catalyst for much of the research and many of the publications of these distinguished professionals and many others.

It is international organizations like IAH and the International Association of Engineering Geology and the Environment that were also a factor in bringing Petar, and Perm State University colleagues Nikolay Maksimovich and Olga Meshcheriakova, together to write this book. Russian professionals have performed many investigations of dam construction in karstified rocks, and many of the publications therefrom are subsequently in Russian and English. I also had the pleasure to become familiar with Nikolai through the chapter he authored in Hypogene Karst Regions and Caves of the World (2017, Springer). It is a companion to this book in the Cave and Karst Systems of the World Book Series of which I am the editor and Springer is the publisher.

At the recent Karst Symposium: Expect the Unexpected in Trebinje, Bosnia–Herzegovina, I had the opportunity to interact with Petar, Nikolai, Olga, and Derek Ford when they were working on the final draft of the book. Discussing their findings firsthand revealed the critical nature of these concerns and what has been done and is yet to be done to address them.

Perhaps the final item to cover in my forward is the accolades and best wishes that were bestowed upon Petar at this symposium. Professionals from around the world came together to celebrate Petar's 80th birthday and present him with gifts unique to his work and/or their friendships. When you experience this outpouring of admiration and acknowledgment of one man's contribution to the field, you know that what you are about to read is a singular tome.

Tuscaloosa, AL, USA — Jim Lamoreaux

Preface

Dam construction in karstified rocks cannot be treated as a routine undertaking. Due to the nature of karst, the differences of significant geological properties from the norm in other rocks are so extensive that they make each dam construction job exceptional. Particularly exceptional, sometimes highly problematic, is the construction of dams and reservoirs in rock formations that include even minor proportions of evaporite rock deposits.

From the beginning of the twentieth century, a number of dams and reservoirs 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, others were abandoned, and some reservoirs suffered severe pollution of the stored water with solutes. Numerous dams in evaporites, mostly in gypsum, have needed costly rehabilitation. The large amount of experience accumulated during these works has been presented in many different references and languages, chiefly in English and Russian. Many of these papers and reports are not easily accessible to the wide spectrum of professionals working in dam geology today. A major purpose of this book is to summarize and present them in a concise form. Particularly important are examples of dam failures due to the conventional grouting technologies proving to be inadequate despite the high quality of remedial works (mostly grouting) undertaken. As a consequence of the high solubility of evaporites, the watertight resistance of grouting structures can quickly become reduced or eliminated by post-grouting processes. To minimize the impact of these hazardous post-grouting processes, different grout mixes and chemical components have been analyzed in laboratories and tested at sites. Because, currently, there are many dam projects under construction or in the design or investigation phases that are located in areas directly or indirectly influenced by evaporites, and the list of problem dams presented in this text cannot be final.

The book is organized into nine chapters. The first four chapters cover general information, including the global distribution of evaporite formations, the properties and processes of karstification as well as an explanation of the different karst forms that may develop in evaporites. Chapter 5 presents the most frequent geohazards associated with dams and reservoirs in evaporite rocks. Chapter 6 describes the range of geotechnical methods frequently applied to improve the evaporite rock mass during the construction of dams and the remediation of their foundations while they are in operation. There is a particular focus on rock waterproofing by grouting and the development of new techniques to construct grout curtains resistant to post-grouting destructive processes. The most frequently applied methods for investigating the basic hydrogeological and geotechnical properties of new sites are described in Chap. 7. Due to the rapid increase of bedrock solution rates that is to be expected during and after the reservoir head rises to the design elevation, the importance of carefully designed monitoring is discussed in Chap. 8. The final Chap. 9 contains a list of more than 80 dams known to the authors that are located on evaporites with brief summaries of 50 of them. The presentation of case studies is not evenly balanced because the levels of information available vary a great deal; for some, there is only basic information, while others can be presented in detail. The work concludes with a list of 245 key references pertaining to the specific topic of dams and reservoirs in evaporites treated in the book.

The authors gratefully acknowledge Dr. Derek Ford, Emeritus Professor, McMaster University, Canada, for his great efforts and help in reviewing this manuscript. We would like to express lot of thanks to him for editing the language in the manuscript in detail and for many of his valuable suggestions and instructions to improve the quality of the book.

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January 2019

Introduction

Sulfate rocks, particularly gypsiferous formations, at the surface or in the subsurface under younger deposits, cover large regions of the world. According to Maximovich (1962), the continental extent of gypsiferous rocks globally is approximately 7 million km^2; Ford and Williams (1989) estimated that gypsiferous and salt deposits underlie about 25% of dryland areas. According to Klimchouk et al. (1997), gypsum karst is more common in the northern hemisphere but is to be found everywhere, from the cold Arctic to the hot arid or humid tropical areas. Sulfate rocks underlie 35–40% of the USA territory, Quinlan et al. (1986). Gorbunova (1977) estimated that 5 million km^2 of the former USSR territory are underlain by sulfate rocks. The total outcrop of gypsum formations in Iran is about 80,000 km^2, i.e., 5% of the total area of that country, Raeisi et al. (2013). Cooper and Calow (1998) listed 80 countries as major world producers of gypsum products.

Many dams and reservoirs all over the world constructed on geological formations containing evaporites have encountered significant seepage or stability problems during their construction, first filling, or later during their operation. Numerous dams in the USA have had serious dissolution problems, sometimes ending in complete failure, as well as dams in Spain, China, Russia, Algeria, Iran, Venezuela, Argentina, Germany, Guatemala, Tajikistan, and a few other countries. All these problems are consequences of the high solubility of the common evaporite rocks, which are chiefly gypsum and salt, with carnalite, sylvite, and glauberite being less common. In many cases, failures could not be prevented or avoided despite the application of massive (and costly) protective measures to try to prevent or halt dissolution. The impoundment of a reservoir can cause rapid dissolution due to the rapid, non-natural, increase of the hydraulic head, often leading to the development of solution cavities in the dam foundations and adjoining areas, collapse sinkholes in the reservoir bottom and its near environs, while slope instability is common along the reservoir banks. These processes can provoke rapid increases in the permeability of the evaporite rock mass and reductions of its mechanical strength. Once the rapid solution has started due to increased hydraulic head at a site, additional protective measures become extremely complicated technically.

During the last decade of the nineteenth century, intensive construction of dams and reservoirs began in karst regions all over the world. The result was an expensive failure in many cases, particularly where the foundation rock masses contained evaporites. In many of these cases, the planned reservoir never filled up, despite extensive investigations and remedial works. Due to the presence of evaporites in the foundations, some sites were abandoned before any building, but in many other instances the dam was constructed, with disastrous consequences. One of the earliest reported problems due to the presence of evaporites was unacceptable seepage losses from the McMillan Reservoir, New Mexico, USA, immediately after its construction in 1893, Cox (1967). A dam in Estremera (Guadalajara) failed in the 1950s due to the karstification of the gypsum bedrock overlaid by alluvial deposits, Gutierrez et al. (2003).

In "Gypsum-karst problems in constructing dams in the USA," Johnson (2008) concluded that if gypsum karst features are present at a dam site or reservoir can compromise the ability of the dam to hold water in a reservoir and can even cause its collapse. "Gypsum karst in the abutments or foundation of a dam can allow water to pass through, around, or under a dam, and solution channels can enlarge quickly, once water starts flowing through such a karst system." These conclusions are confirmed at a number of dams and reservoirs built in evaporites around the world.

For instance, the worst American civil engineering failure of the twentieth century was that of the St. Francis Dam (California, USA) that killed 432 people along the St. Francisco Canyon and Santa Clara Valley in March 1928 (Ransome 1928). According to Cooper and Calow (1998), the strong uplift that displaced much of the dam with catastrophic rapidity was attributable partly to gypsum dissolution. The Quail Creek Dam (Utah) was constructed in 1984 and failed in 1989 due to the creation and enlargement of caverns in its foundations. More recently, the Mosul Dam, a very important water control structure in Iraq, has been declared to be the most dangerous dam in the world because of the history of nearly continuous, massive grouting works needed during the 30 years or more since its construction was completed, works that have failed to eliminate continuing dissolution beneath it (Sissakian et al. 2014).

In practice, every dam and/or reservoir that is constructed in geological formations containing evaporites will face at least one of the three principal problems: ***seepage losses, instability of dam foundations and reservoir banks, and water pollution***.

Different aspects of the problems with dams and reservoirs in evaporites are discussed by: Ransome 1928; Maximovich G.A. 1948; Jiménez 1949; Maslov and Naumenko 1958; Brune 1965; Liamas 1965; Gunnar 1965; Cox 1967; Calcano and Alzura 1967; Mamenko 1967; James and Lupton 1978; Pechorkin and Pechorkin 1979; Klizas and Maksimovich 1979; James and Kirkpatric 1980; Voronkievich et al. 1983; Maximovich N.G. 1986, 2006; Anagnosti 1987; Hu 1988; Ford and Williams 1989, 2007; Gorbunova et al. 1991; Guzina et al. 1991; Araoz Sánchez-Albornoz 1992; Lykoshin et al. 1992; James 1992; Lu and Cooper 1997; Cooper and Calow 1998; Pearson 1999; Dreybrodt et al. 2001; Romanov et al. 2003; Gutierrez et al. 2003, 2015; Johnson 2003, 2004, 2008; Milanović 2004, 2011, 2018; Lu and Zhang 2006; Kiyani et al. 2008; Moradi and Abbasnejad 2011; Manchebo Piqueres et al. 2011; Barjasteh 2012; Cooper and Gutiérrez 2013; Sissakian et al. 2015; Mahjoob et al. 2014; Meshkat et al. 2018; Maximovich and Meshcheriakova 2018.

In addition, the authors of many other articles concerned with the nature of evaporite deposits (at local to global scales) include remarks focused on dam construction in these hazardous environments. Dam problems in evaporites are reported in a number of different scientific journals and have presented at many international conferences and congresses in Russia, China, USA, Turkey, Iran, etc., organized at the international level by the International Association of Hydrogeologists (IAH) and the Commission Internationale des Grandes Barrages (ICOLD), or by national scientific organizations such as the Molotov (Perm) Karst Conference in Russia (1946), First world congress on Public Works Constructed Over Gypsum, Madrid, 1962, the influential series of fourteen quadrennial Multidisciplinary Conferences on Sinkholes (USA); the conference on Engineering Geological Problems of Construction on Soluble Rocks (Istanbul, 1981). Six karst conferences that include an emphasis on engineering problems have been organized in Turkey (1977, 1979, 1985, 1990, 1995 and 2000), two in Iran (1983 and 1998), and a few in China (1988, 2001, 2006, 2013). A theme section on engineering problems in Evaporite Karst was held in Denver (2002) as part of annual meeting of the Geological Society of America. Over the past two decades, similar conferences were organized in Belgrade (Serbia, 2005), Malaga (Spain, periodically from 2010), Perm (Russia, 2004, 2015), Dzershinsk (Russia, 2007, 2012), Besançon (France, 2011), Ufa (Russia, 2012), DIKTAS Conference—Karst without Borders (Trebinje, Bosnia and Herzegovina, 2016) and Neuchâtel (Suisse, Euro karst 2016). International journal Carbonates and Evaporites, established in 1979, provides a specialized forum for the exchange vide spectrum of experience including engineering issues in karstified rocks.

Interest in the geological properties of evaporites has increased because of the many geotechnical problems arising from the high solubility. The most frequent and most common problems are subsidence caused by groundwater abstraction, and leakage beneath the dam due to solution channels forming in these rocks. The technical and financial losses including losses of human lives have caused increasing concern with building large structures in these environments. A few scientific projects have been launched to better understand evaporites and to develop effective methods of prevention and remediation to minimize the geohazards. "Avoiding gypsum geohazards: Guidance for planning and construction" was funded by the UK Department for International Development, 1998. "Research on the Development Mechanism of Sulphate Rock and Impacts of its Environmental Evolution" was supported by the National Natural Science Foundation of China, 1999–2001.

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