Development of Sulphate Karst Under Technogenic Impact Conditions in the Western Urals

Nikolay Maksimovich and Olga Meshcheryakova

Abstract

The manuscript is devoted to the influence of sulphate karst on engineering structures and the environment. Karst processes are intensified under anthropogenic impact; this fact needs to be considered in the design, construction and operation of various constructions or technical sites. Impact of sulphate karst was studied by the example of the Kama hydroelectric power station, at the base of which gypsum rocks lie, and also in the area of the Polazna oil field.

P. Renard, C. Bertrand (Eds.), *EuroKarst 2016, Neuchâtel*, Advances in Karst Science,
DOI 10.1007/978-3-319-45465-8_7

7.1 Introduction

Karst rocks such as limestone, gypsum and salt are developed within vast areas of the Western Urals. Modern and ancient karst is widespread there.

Perm region is situated in the Western Urals (Russia) and occupies an area of about 160,000 km^2.

The Paleozoic gypsums, anhydrites, salts, limestones, dolomites and more rarely the Proterozoic carbonate rocks occur in Perm region either at a low depth under the surface or crop out within an area of more than 30,000 km^2 (Gorbunova et al. 1990).

Three geological structures are present in this area: the eastern margin of the East European Platform, the CisUrals Foredeep and the folded zone of the Urals. Mainly sulphate karst and, to a lesser extent, carbonate karst occur on the Platform. Salt and gypsum karst develops in the Foredeep; whereas dolomite and limestone karst and somewhere marble karst are registered in the folded zone of the Urals. Karst rocks are covered by eluvial and deluvial deposits; in river valleys, they are overlapped by alluvial deposits or non-karstic rocks of a relatively small thickness. Seldom they are uncovered.

The territory of the Western Urals in the whole and Perm region, in particular, undergoes strong technogenic impact, which alters significantly the conditions and factors of karst development due to irreversible transformation of relief and rocks, pollution of surface and groundwater, as well as vegetation degradation. Particular attention should be paid to the area of gypsum karst distribution.

7.2 Problems of Sulphate Karst

Problems associated with sulphate karst though not so widespread are significant; its activity is ten times higher than carbonate karst. Deformations of the earth's surface are characteristic for the area with the development of sulphate karst and constitute great danger for engineering structures.

7.2.1 Gypsum in Foundations of Hydraulic Structures

The presence of soluble rocks, such as gypsum, in the foundations of hydraulic structures causes unfavourable engineering geological conditions for the safety of constructions (Klimchouk and Andrejchuk 1996; Cooper and Gutiérrez 2013).

Gypsum rocks in the base of the Kama hydroelectric power station, which is located in Perm, have created serious problems. Similar problems were observed in different regions of the world.

Hydrotechnical construction in such soluble rock regions may create conditions of enhanced dissolution and karst development that may threaten engineering structures. Throughout the world, there are cases, when the dissolution of gypsum in dam foundations led to tragic consequences. The failure of the St. Francis dam in California, USA, is one catastrophic example, where 400 people perished as a result. Numerous problems such as settlement, cracking and seepage with the constant threat of failure or expensive remediation are associated with dams on gypsum. For example, in the vicinity of Basel, on the Birs River, the dissolution of gypsum beds in the dam foundation caused settlement and cracking. Settlement was also observed on the San Fernando, Olive Hills, and Rattlesnake dams in California (Ford and Williams 1989; Milanovic 2000; Maximovich 2006).

Water loss from water reservoirs on gypsum rocks is common and seepage through the dam foundations were recorded on the Osa River (Angara basin), in Oklahoma and New Mexico (USA). Seepage and gypsum dissolution form cavities, and these features have been found in the foundations of the Hondo, Maximilian and Red Rock dams, along with a dam in the Caverly valley, Oklahoma. Gypsum also occurs in the foundations of the San Loran dam in Catalonia, Poechos dam in Peru and a number of dams in Iraq (James and Lupton 1978; James and Kirkpatric 1980).

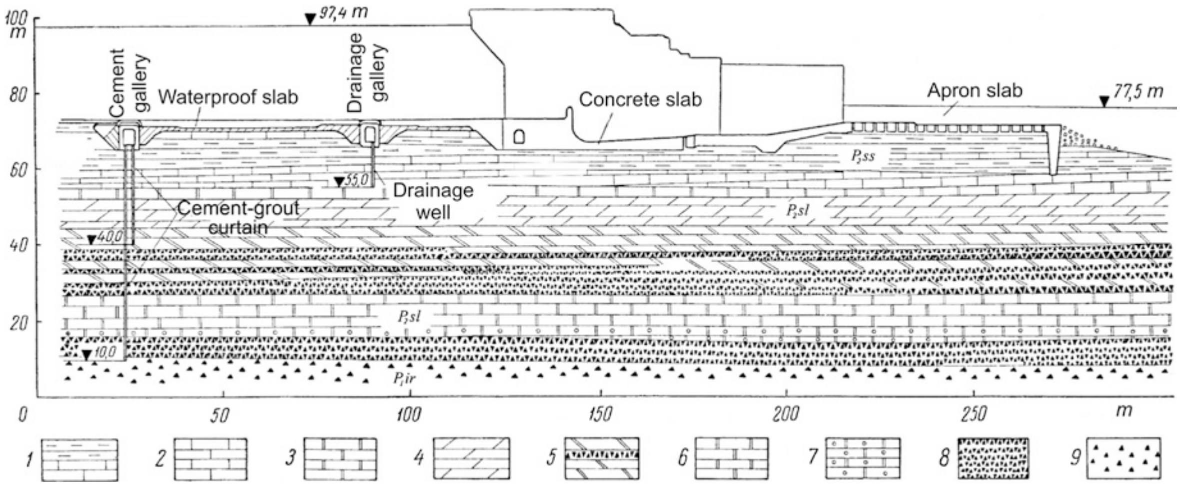
In a number of cases, the presence of gypsum rocks resulted in the rejection of the dam site for construction. For example, this was the case of Saint Baume dam in Provence, which was found on gypsum marls. Survey for the Rian dam in the vicinity of Alter Stolberg, the south of Harz, stopped after gypsum was discovered in the foundation zone.

More than 50 dams have gypsum in the foundations. Salt rocks, which are more soluble, have been found in the basis of other dams including the Rogunskaya, Nurekskaya dams on the Vahsh River in Tajikistan, as well as the Kama hydroelectric power station on the Kama River in Perm (Russia).

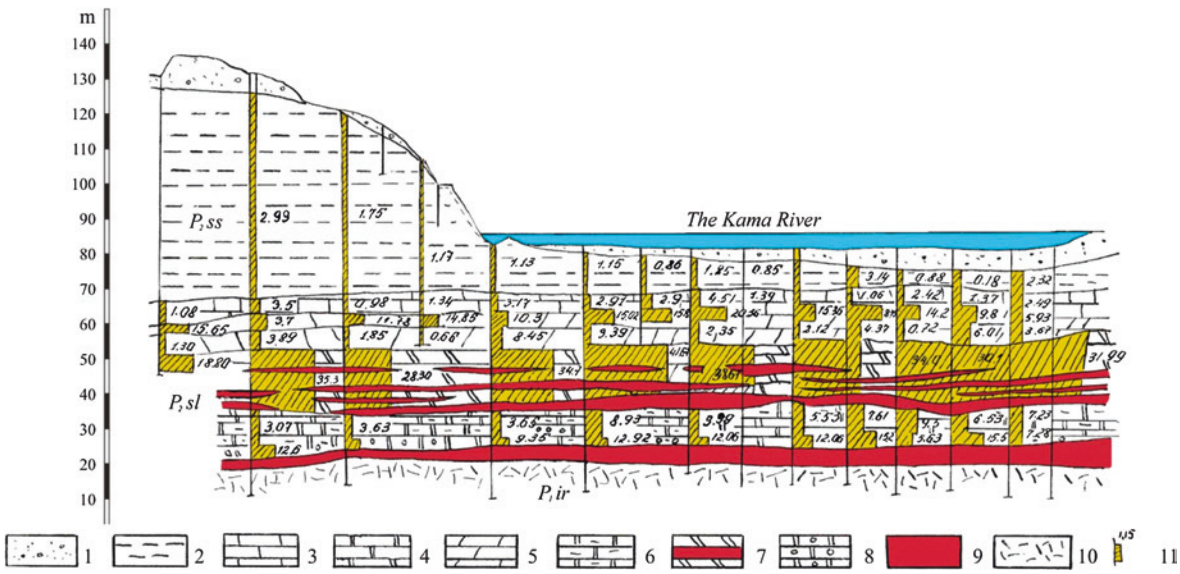
The base of the Kama dam is formed by Sheshmin sandstones, siltstones, mudstones, which are replaced by the lower Solikamsk limestones, marls, dolomites with lenses of gypsum. Irenian horizon consists of gypsum, anhydrite, limestone and dolomite. Gypsum and anhydrite lie above (Figs. 7.1 and 7.2).

These deposits are covered by non-karst rocks in the area of the dam base, which prevents the development of karst, but there are numerous karst forms on the reservoir banks.

The rate of rock dissolution depends on the amount of seepage through the rock. One way to reduce this water movement is to create a grout curtain.



◘ Fig. 7.1 Geologic section of foundation of Kama hydroelectric power station. P_{2ss} Sheshmin horizon: *1* mudstone, siltstone with limestone; P_{2sl} Solikamsk horizon: *2* limestone, *3* dolomite, *4* marl, *5* marl and dolomite with gypsum, *6* dolomite, *7* dolomite clayey; P_{1ir} Irenian horizon: *8* gypsum, *9* anhydride



◘ Fig. 7.2 Content of gypsum in rocks of Kama dam foundation. *1* sandy–pebble sediments and under floodplain terrace, *2* mudstone, siltstone with limestone, *3* limestone, *4* dolomite, *5* marl, *6* dolomite, *7* marl and dolomite with gypsum, *8* dolomite, *9* gypsum, *10* anhydride, *11* average content of gypsum (%)

The grout curtains in jointed rocks are created by injecting cement or cement–clay grout that permits reducing the specific water seepage to 0.10–0.05 l/min.

Lower values cannot be obtained because cement suspension grouts cannot penetrate into cracks which are less than 0.1 mm wide. The operation of the Kama hydroelectric power station showed that these residual cracks allowed water seepage and leaching of the gypsum. This dissolution and an increase in the size of joints caused a drop in the percentage reduction of head on the grout curtain in some zones to as little as 2–4 % compared to a design value of 33 %.

Chemical gel-forming solutions with a penetration capability close to that of water have been recently introduced to increase the density of grout curtains made in finely jointed gypsum rocks. Oxaloaluminosilicate was used for additional solidification of the grout curtain in the fractured gypsum rocks in the foundations of the Kama hydroelectric power station. The solution comprises two components—sodium silicate with a density of 1.19 g/cm^3 and a hardener. The complex hardener is an aqueous solution of aluminium sulphate and oxalic acid. As a result of using the oxaloaluminosilicate solution, the specific seepage through the curtain does not exceed 0.005 l/min. This mitigated the head reduction at the grout curtain and increased the dam stability to a safe level (Maksimovich and Sergeev 1983).

The use of chemical reagents for grouting raised the question of their effect on the stability of gypsum. This effect, in addition to the direct contact of the gel with the rock, occurs beyond the limits of the stabilization zone. It happens during the injection in the peripheral parts, where the chemical gel-forming solutions are diluted with water to the extent that they cannot form a gel. The seepage carries these diluted chemicals beyond the limits of the curtain where during the movement they undergo further dilution. Consequently, solutions of variable dilution are brought into contact with a large surface area of the gypsum rock. Components of the injection solution also pass from the gel grout into the seepage flow by diffusion, and these can impact the gypsum.

It was established that solutions containing components of the oxaloaluminosilicate formulation have a beneficial effect on interacting with gypsum. The chemicals not only do not dissolve gypsum, but also form a protective surface film of low-soluble calcium oxalate and calcium hydrosilicates; these films protect gypsum from dissolution.

7

7.2.2 Gypsum Karst in Oil Fields

The Perm region is one of the areas of oil deposit development. A considerable number of them are located within the drainage area of the Kama River. In this area, the groundwater is poorly protected from pollution due to the intense karst development. Contaminated groundwater is discharged to the water reservoir and pollutes significantly the water reservoir and the adjacent areas. This phenomenon extends largely due to a low protection of the groundwater owing to high karst activity of the region (the average relative density is 60 karst forms per km^2, and solid block cavitation is 30 %).

The Polazna oil deposit is an example of oil-polluted karst region. The deposit area encloses the left coastal side of the Kama water reservoir. In total, 1691 karst forms are mapped within the area of 28.1 km^2 (97 % of them are sinkholes). Other surface forms, such as karrs, karst trenches, hollows, gullies, dry river channels and lakes, are also registered (Maximovich and Meshcheryakova 2009).

The analysis of geological and hydrogeological information proved that oil discharge to the coast is related to the long-term operation of oil deposit. The intense karstification of the area is one of the principal natural factors that provides the development of oil pollution at the surface of fracture-karst water.

The oil lens has been formed during exploitation of oil deposit. Its width is approximately 2 m. Atmospheric precipitation, which filtrates throughout the lens, pollutes groundwater and then contaminates water in the Kama reservoir.

For improving the ecological conditions, the technology of mechanical and microbiological purification of polluted water has been elaborated and licensed.

The special equipment for pumping oil out of the lens through the boreholes was elaborated, tested and licensed. The main idea of this method is pumping oil without water removal. This aim was achieved. All technologic elements such as sensors of lens depth and capacity, possibility of operative changes of pump depth were examined. It was shown that the borehole discharge allowed pumping oil in great volumes, i.e., about 200 l/h.

The second method is based on using microorganisms. The groundwater provides a habitat for bacteria. Microorganisms in groundwater are active in situ and affect groundwater chemistry and quality. Subsurface environmental factors such as temperature, pH, redox potential, availability of electron acceptors, salinity and hydrostatic pressure, porosity of the aquifer's rocks, chemical recalcitrance and solubility, chemical and physical adsorption and desorption on rock particles influence the microbial activity and, therefore, also the transformation of pollutants. Microorganisms found in groundwater transform a large number of contaminants under the existing redox conditions (Fig. 7.3). The presence of sufficient electron acceptors will be a principal factor in predicting the degradation of organic contaminants in aquifers (Elmen et al. 1997). Other elements like Mg^{2+}, K^+, Ca^{2+} and trace elements necessary for microbial growth are usually available in quite enough concentrations to support microbial growth.

The most common pollutants of groundwater are hydrocarbons and heterocyclic compounds of oil and oil products. There are two main biotechnological methods of oil-polluted natural habitats remediation: the stimulation of natural microbial hydrocarbon-oxidizing populations by nutrient supplies (especially nitrogen and phosphorus); and the introduction of active hydrocarbon-oxidizing bacteria (and nutrient supplies) into polluted environments (McNabb and Dunlap 1975).

The authors in collaboration with V. Khmurchik combine these approaches to achieve purification of oil-polluted karst aquifer. The work consists of several stages: the isolation of active hydrocarbon-oxidizing bacteria from karst groundwater and the investigation of their oil

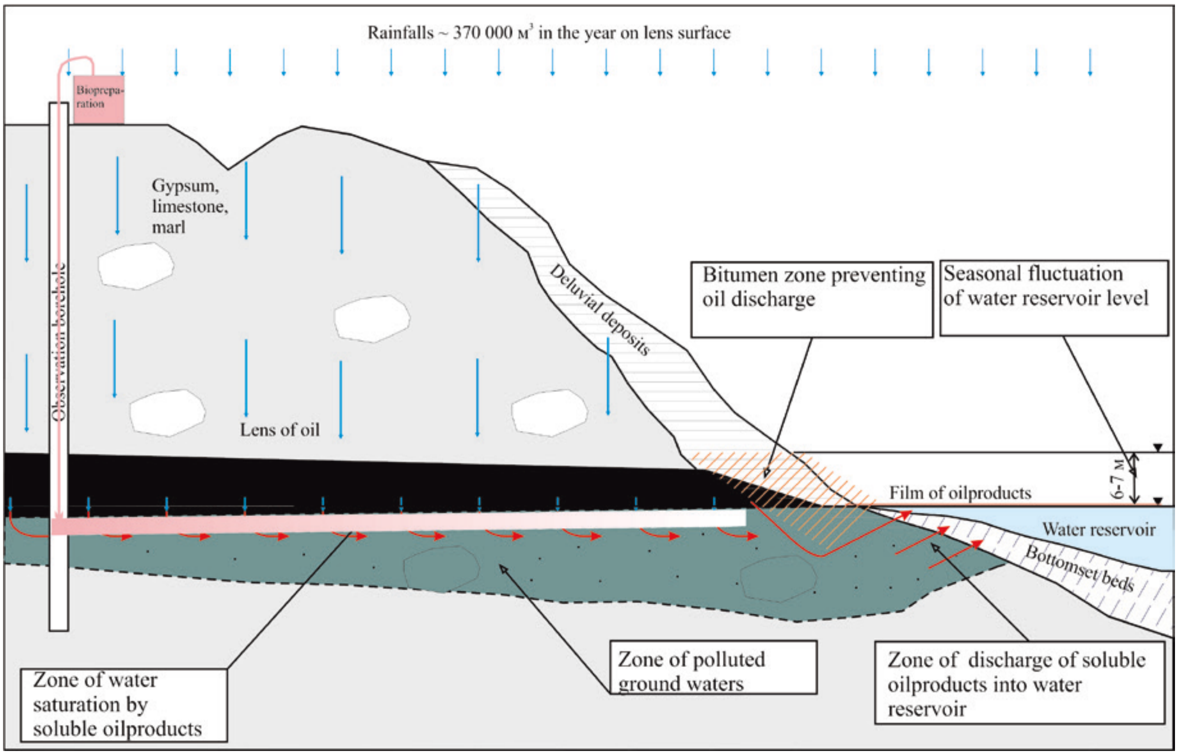


Fig. 7.3 Scheme of processing oil lens by biopreparation

degrading capability; the development of bacterial preparation based on isolated aboriginal hydrocarbon-oxidizing bacteria to remediate oil-polluted groundwater; the stimulation of aquifer's hydrocarbon-oxidizing microflora by inorganic nutrients supplies; and the introduction of developed bacterial preparation into the aquifer to achieve complete oil removal (Maksimovich and Khmurchik 2014).

The introduction of actively metabolizing hydrocarbon-oxidizing bacteria into polluted environments is essentially actual in the regions of cold and temperate climate, where the warm season is not long.

7.3 Conclusions

Consequently, the example of a small region has shown that the presence of karst rocks especially on territories with high technogenic influence causes various and significant problems for engineering structures and environment. That is why specific protective works are required for mitigating negative consequences and reducing great expenses for its elimination.

Acknowledgments This work was financially supported by the Russian Foundation for Basic Research (Project 16-35-00104 mol_a "Migration of hydrocarbons in the filtration and diffusion transfer in karst areas") and was financially supported by the Russian Ministry of Education (the state task No. 2014/153 No. 269).

References

Cooper, A.H. and Gutiérrez, F. (2013): Dealing with gypsum karst problems: hazards, environmental issues and planning, Treatise on Geomorphology, Vol. 6, Karst Geomorphology, pp. 451–462.

Elmen, J. et al. (1997): Kinetics of toluene degradation by a nitrate-reducing bacterium isolated from a groundwater aquifer, Biotechnical Bioengineering, No 55, pp. 82–90.

Ford, D.C. & Williams, P.W. (1989) Karst geomorphology and hydrology, Chapman & Hall, London.

Gorbunova, K.A et al. (1990): Technogenic impact on the Karst in Perm region, Studia carstologica, No 2, pp. 37–43 (in Russian).

James, A.N. & Kirkpatric, I.M. (1980): Design of foundations of dams containing soluble rocks and soils, Quart. J. Engineering Geology, Vol. 13, No 3, pp. 189–198.

James, A.N. & Lupton, A.R. (1978): Gypsum and anhydrite in foundations of hydraulic structures, Geotechnique, Vol. 3 (28), pp. 249–272.

Klimchouk, A. & Andrejchuk, V. (1996). Environmental problems in gypsum karst terrains. International Journal of Speleology, No 25(3), pp. 145–156.

Maksimovich, N.G. & Khmurchik, V.T. (2014): Remediation of Oil-Polluted Groundwater Aquifers at Karst Region, Engineering Geology for Society and Territory, Vol. 3, River Basins, Reservoir Sedimentation and Water Resources, pp. 417–419 (in Russian).

Maksimovich, N.G. & Sergeev, V.I. (1983): Effect of chemical injection stabilization on gypsum stability in the foundation of hydraulic structures, Power Technology and Engineering, Vol. 17, No 7, pp. 380–384 (in Russian).
Maximovich, N.G. (2006): Safety of dams on soluble rocks (The Kama hydroelectric power station as an example), Perm, 212 p (in Russian).
Maximovich, N.G. & Meshcheryakova, O.Y. (2009): The influence of gypsum karst on hydrotechnical constructions in Perm region, Proceedings of the International Symposium of IAEG, China, Vol. 2, pp. 604–607.
McNabb, J.F. & Dunlap, W.J. (1975): Subsurface biological activity in relation to groundwater pollution, Groundwater, Vol. 13, pp. 33–44.
Milanovic, P.T. (2000): Geological in Karst: dams, reservoirs, grouting, groundwater protection, water tapping, tunneling. Belgrad, 347 p.