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GROUND-WATER AS A NUISANCE

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ABSTRACT

In certain circumstances, ground-water causes geotechnical problems and can be considered a nuisance rather than a blessing. The cases where ground-water creates considerable complications include construction, tunnelling, mining, landslides, and land subsidence. The development of hydrogeology as a science has proved over the years to substantially reduce the severe problems and disasterous problems caused by ground-water.

INTRODUCTION

Ground-water is considered one of the earth's most widely distributed and most valuable resources. Utilization of ground-water through construction of wells and infiltration galleries in ancient times is well known from the biblical record of Genesis. In all ages throughout the history of mankind, the civilizations and agriculture have flourished when water supplies were available.

In the human mind, ground-water is considered mostly as the elixir of life; very seldom is ground-water considered and described as a nuisance. However, there are many circumstances where ground-water is causing considerable complications calling for tremendous human efforts in solving them, and there are many cases where ground-water has been responsible for disasters involving great losses of life and considerable economic losses. This pertains especially to the ventures where underground excavation is involved. Mining and tunnelling are the two most typical examples where overcoming either slow and/or sudden water inflows has been a great problem in the history of these human activities.

In the following paragraphs several cases of ground-water acting as a nuisance are discussed. In most of these cases, where ground-water caused either a disaster or led to severe complications for a particular project, the problems could either have been eliminated altogether or their impact been reduced with a sound knowledge and assessment of the hydrogeologic conditions of the project site. Nowadays, the involvement of an experienced hydrogeologist in projects with anticipated ground-water problems has become vital and indispensable.

GROUND-WATER AS A NUISANCE

Generally, geotechnical problems created by ground-water arise as a consequence of excessive rates and quantities of ground-water inflow.

The presence of ground-water is a typical feature in all sorts of excavations. Any excavation that must be done below the water table will encounter ground-water flow. However, even shallow excavations or building foundations above the water table may become flooded by ground-water after prolonged periods of excessive recharge to ground-water, which result in a rise of the water table.

The location of urban developments or small communities in alluvial valley floors or local streams is very common. The water table in alluvial sediments is typically shallow and its fluctuation depends on several factors. The major part of ground-water recharge into the alluvial aquifer is, in most cases, provided by direct infiltration of water from the stream. In cases of flooding, even when the surface stream remains under control, the excessive recharge to the aquifer can cause a sudden rise of the water table above the normal level and lead to considerable damage by flooding basements in low elevation areas, by impacting stability and integrity of foundations and river banks, etc. The flooding of basements, farmland, or other communal areas is not as spectacular in its consequences as ground-water related disasters in mining or tunnelling. However, considerable economic losses are experienced by flooding caused by ground-water.

The most obvious and dramatic example of the detrimental effect of ground-water is its inflow into excavations. The excessive presence of ground-water during excavations for foundations and tunnels and during the opening of surface or underground mines can cause serious complications in the operation and lead to increased expenditures. The impact of mining on ground-water resources and vice versa is the object of many studies and litigations.

Other problems, such as land subsidence and slope instability, arise from the change of fluid pressures in the ground-water rather than from the rate of ground-water flow itself. Pore pressure can change naturally as a consequence of excessive recharge or artificially as a consequence of excessive withdrawals of ground-water. An excessive recharge of certain strata and increased pore pressure very often causes instability of natural and man-made slopes and can trigger landslides. In the earth and rockfill dams pore pressure can develop from an uncontrolled ground-water flow through the dams. However, these problems are usually analysed and taken care of during the design of a dam.

One of the last obvious and least understood forms of negative impact of ground-water is its role in the generation of earthquakes, which in concept is similar to that in the generation of landslides. The fluid pressures that build up on faults are now thought to have a controlling influence on fault movements and the generation of earthquakes [1].

Excessive withdrawals of ground-water by pumping for the purpose of irrigation or other water supply or for mine dewatering has caused severe surface subsidence problems in many instances. Land subsidence is the result of a decline in ground-water levels or a reduction of artesian pressure, and it is usually a slow and gradual process. However, catastrophic land subsidence leading to the formation of sinkholes in soluble rocks can also be associated with a decline in ground-water levels.

GROUND-WATER IN CONSTRUCTION AND TUNNELLING

The impact of ground-water on construction and tunnelling projects can be considerable. Ground-water inflow and the presence of ground-water have an impact on the design, construction or excavation procedures, the selection of construction materials, the schedule of the project, and consequently, on the overall project costs. There have been many cases where unexpected problems caused by the ground-water inflow required substantial changes in design and caused major delays in the completion of the project. In some instances, entire projects were abandoned because of water inflow problems entailing a considerable financial loss. A high proportion of consequent claims and litigation in construction contracts arises from the very same ground-water problems [2]. However, ground-water problems encountered during construction, excavation, and foundation work do not have the same spectacular effects as those caused by the inflow of ground-water during tunnelling.

Inflows of substantial quantities of ground-water during the advancing of tunnels have created many difficult problems in history of tunnelling. The problem does not merely lie in the inconvenience of working in a wet environment. The presence of even small quantities of water in certain unconsolidated strata and in open joints of dense rock can cause instability and eventually collapse of the tunnel walls. A number of disasters involving many casualties during tunnelling can be directly related to the ground-water inflow.

According to Beaver [3], "the greatest and most common danger in tunnelling is water, which can suddenly appear in enormous quantities no matter what type of ground is being traversed". Describing the building of the 5.63-km Totley Tunnel in the 1890s, the Manchester Guardian remarked that "every man seemed to possess the miraculous power of Moses, for whenever a rock was struck, water sprang out of it". Though not all tunnels driven below the water table have large ground-water inflows, the following cases elaborate on the danger and the complications caused by ground-water.

Although the first tunnels were driven as far back as the Prehistoric and Bronze Age - primarily for the purpose of digging out a shelter and later to mine flint and metals - it is highly probable that ground-water was not a concern during that early stage of tunnelling. The tunnels for drainage and water supply during the Roman period are well known. However, the documentation of that period does not contain any data pertaining to ground-water problems.

One of the results of the industrial revolution was the construction of the first modern tunnels as a means of transportation. During that period, the first subaqueous tunnel, the Thames Tunnel (1824-1842), was completed in England. During the construction of this tunnel the water flooded it five times, and during one of the water inrushes six men drowned. The pumping of water and the cleaning of soil washed into the tunnel caused a great delay in the completion of the project and increased the cost accordingly [4].

The Kilsby Tunnel of a length of about 2.2 km on the Liverpool-Manchester railroad line was possibly the first tunnel driven with the help of systematical dewatering. During the completion of this tunnel, an eight-

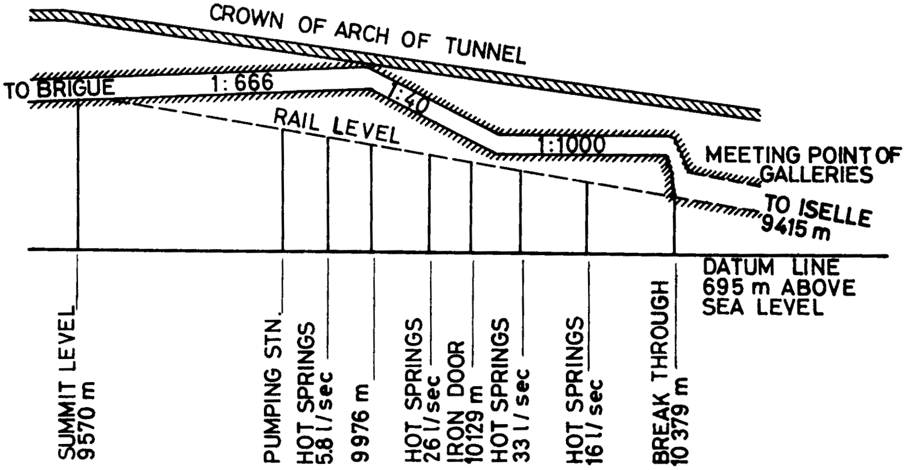


Figure 1 Method of breakthrough in Simplon tunnel chosen due to hot water inflow (from Sandström, 1963).

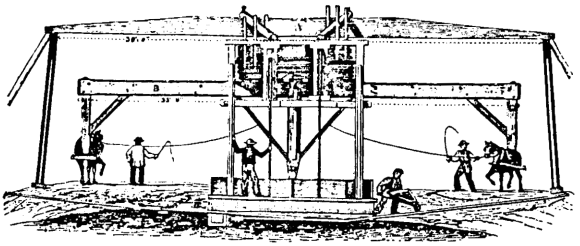


Figure 2 Horse gins for winding (from Harding, 1981)

months delay was caused by ground-water inflow. The water level was lowered by a series of pumps working simultaneously, connected by a series of bars to a steam engine [4].

In the middle of the 19th century a great tunnelling effort reached the Alpine countries. The successful completion in 1871 of the first tunnel, the Frejus Tunnel, 12.07 km long, connecting France and Italy, initiated the construction of a series of Alpine tunnels.

The construction of the Simplon Tunnel encountered severe ground-water problems. According to Sandstroem [5] serious trouble developed in this tunnel after reaching 4.43 km in the southern heading. "In the No.1 tunnel, the mining team struck a spring, which flooded the heading with 125 l/sec and necessitated abandoning the drilling machines. In order to get rid of the water, a cross-heading was driven 2.74 m in the rear, where another spring was struck and poured a further 167 l/sec into the heading. In the No.2 pilot heading, a third spring was encountered that produced 386 l/sec. An underground basin had obviously been tapped, and the miners were astounded to see 60°C hot water rising, while a few feet away a column of 15°C water was descending. They were probably the first human beings to watch the hydraulic forces actually at work shaping the earth's crust." Owing to the danger of flooding the southern heading by hot water, a unique method of breakthrough, as shown in Fig.1, was chosen for the Simplon Tunnel.

Although most of the Alpine tunnels had numerous casualties in their history caused by different reasons, the worst disaster in Alpine tunnelling caused by ground-water occurred during the construction of the Loetschberg Tunnel in Switzerland. This tunnel, completed in 1912, is 13.7 km long and connects the city of Brig with Frutigen in the Bernese Alps. After driving a length of 2.68 km, the tunnel reached a contact between solid limestone and alluvium of the Kander Torrent 201 m above. With the force of over 200 m of hydraulic head, ground-water filled the tunnel and none of the mining crew of 25, present in the heading, lived to give evidence of what had actually happened, since within seconds, they were buried in an avalanche of boulders, silt, mud, and sand (Sandstroem [5]). This disaster was obviously caused by a poor knowledge of the hydrogeologic conditions of the tunnel alignment.

On the North American continent one of the worst mishaps caused by water inflow into a tunnel construction happened during the driving of a railway tunnel under the Hudson River in New York. In July 1880 the construction, using the compressed air method, reached 91.4 m under the river. At this time, with 2.25 atm pressure used for driving, a leak occurred and the compressed air blew a hole through the overburden which was composed of soft silt. Twenty men drowned and eight escaped unharmed (Burr 1885). In 1905, a similar blowout took place in the Rapid Transit Tunnel being advanced under the East River about 61 m from Joralemon Street in Brooklyn, New York. According to Sandstroem [5] there were at the time 8 men in the shield when compressed air blew a hole through the river bottom, which at that place was only 1.52 m above the tunnel crown. When attempting to stop the leak with a bale of hay, a miner was sucked into the hole. For a moment he got stuck in the silt, with only his legs showing below. Eventually the air pressure shot him through the silt and hurled him upward through 4.6 m of water to the surface of the river. There he was rescued, unharmed, by a number of highly amazed longshoremen.

At the Tecolate Tunnel, driven through the Santa Ynez mountains in California during the period 1950-55, the largest ground-water inflow reached 580 l/sec at temperatures of up to 40°C. One inflow at 180 l/sec held up construction for 16 months and resisted all grouting attempts. All flows came from intensely fractured siltstones and sandstones [1].

The San Jacinto Tunnel driven near Banning, California, advanced only about 50 m from the shaft when a heavy flow of water, estimated at 480 l/sec, accompanied by over 760 m^3 of rock debris, flooded the tunnel and shaft. The source of water inflow was, in this case, a fractured fault zone [1].

GROUND-WATER IN MINING

The presence of ground-water in mines has detrimental effects on mining operations, both in surface and underground mines. The existence of ground-water inflow into the excavations limits the mining methods to be used, affects the productivity and cost in many cases, presents hazards, and can cause severe environmental impacts on the ground-water quality and quantity in the area adjacent to the mine.

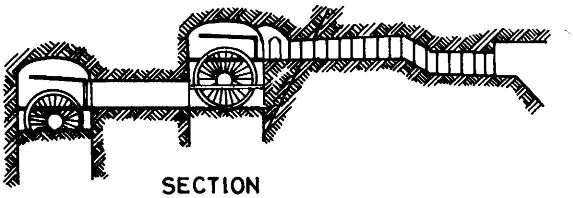
There are many cases to be found in the history of mining where the difference in expenditure between mining in a wet mine and a dry mine were substantial. The following examples demonstrate the detrimental impact of the presence of ground-water in mining: the heavy equipment with rubber tires used in mines does not operate efficiently in muddy or wet conditions; the presence of ground-water in blast holes may necessitate the use of more expensive explosives; excessive moisture in the mined material complicates handling and processing of the ore; the presence of ground-water in both unconsolidated and consolidated materials affects the safety of mining; and finally, the sudden inrushes of water into mines are sources of great danger often leading to a considerable loss of lives.

History of Mine Dewatering

Historically, it is well documented that the initial mining efforts were plagued by ground-water inflows. The first mines were excavated mostly above the local stream bed and the mines were dewatered by means of drainage adits. The first water lifting devices were implemented in the mining fields in Greece and the Middle East in the second century BC. The wooden devices lifted water in buckets fixed on a rope, and were powered by horse gins or overshot weels (Fig.2). This system, with only minor changes, has been in use in the mines until the 17th century.

The Romans introduced several new methods of mine drainage. These consisted of water-raising wheels and cochlea (water snails) or Archimedian screws, both applied for drainage [5]. The sophisticated drainage works developed by the Romans also contributed to increasing the output of the mines. With the drainage devices, as shown in Fig.3, the Romans succeeded in working flooded mines or lowering the levels of ancient workings. In the old Spanish and Portugese copper mines, the Rio Tinto mine in particular, Roman engineers installed a series of 4.6 m water-raising wheels placed above each other at consecutive levels. The wheels were driven by a couple of men treading them with their feet.

The mining rapidly developed in Central Europe between the 12th and 15th centuries. This period of mining and the methods of dewatering are well documented in the Agricola's de re Metallica [6]. This book remained



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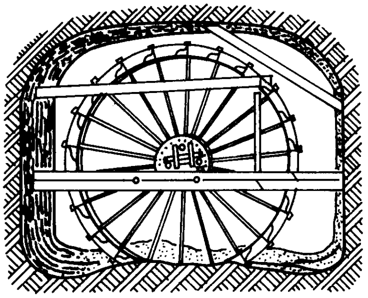

DETAIL

Figure 3 Layout and detail of Roman drainage installation employing water-raising wheels (from Sandström, 1963)

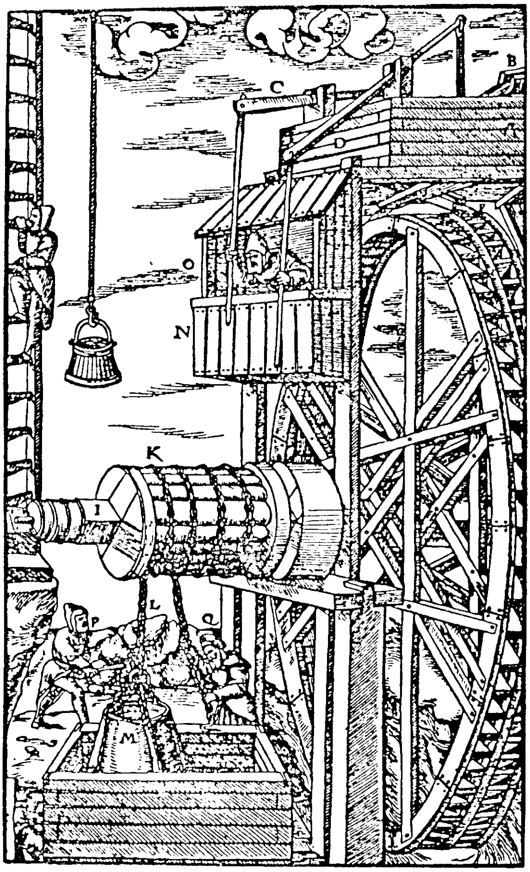

Figure 4 Overshot wheel used for rising water from mines (from Agricola, 1556)

for nearly 200 years the standard handbook on mining and metallurgy. At that time, the water inflow into the mine was controlled by several means: by hoisting the water in leather bags (Fig.4) by pumps, and by drainage adits. There are adits (nearly horizontal passages) from the 12th century as long as 7 km. The largest drainage adit is very probably the Ferdinand adit in Kremnica, Czechoslovakia, which is 18 km long.

A revolution in mine dewatering was achieved with the invention of the steam engine. This invention was applied in the early stage to pump water from the coal mines in Great Britain. The pumping systems in the coal mines were greatly improved by increasing the pumped volumes and delivery head.

Gradual and Sudden Flooding of Mines

Water inflow into the mine may be gradual or sudden. The gradual inflow is not exactly dangerous to life. However, the consequences may be quite detrimental to the mining operation. Ground-water can infiltrate the mine from surface streams or from aquifers. This type of inflow is usually steady, but not uncontrollable. Although there are known mines with ground-water inflow up to 5,000 m^3/h, these inflows can be handled by properly designed pumping stations or other types of mine dewatering techniques. Gradual water inflow typically increases the cost of mining and has a detrimental impact on the mining environment.

A sudden inrush of water is a source of great danger, and many mining disasters with considerable losses of lives have been caused by it. The sources of a sudden water inflow into the mine are faults, abandoned flooded workings, caverns in karstic formations, mine workings entering highly permeable aquifers in the overburden, etc. One such example, showing a combination of faults with inundated old workings, is shown in Fig.5.

Although dangers caused by water account, for example in Great Britain, for only a very small percentage of deaths and injuries occuring in coal mines (on the average 8 deaths per year between 1850 and 1955, and 2.3 deaths and compensable injuries per year on the average for 10 years, 1946-1955 inclusive), there often looms the possibility of disaster from an inrush of water [7].

In the history of coal mining there are many documented cases of sudden water inrushes into the mines that ended catastrophically with many lives lost and great reserves of coal inundated. It is possible to mention only a few of the known disasters because of the limitation of this paper. In 1915, 235 Japanese coal miners lost their lives when sea water broke through along a fault into the mine workings, 72 m beneath the sea (Mohr [8]). In 1923, at Redding in Great Britain, water from an abandoned sump, not shown in maps, entered the mine, killing 40 miners [9]. In the United States, 12 miners lost their lives in 1959 when the flooding of the Susquehanna River broke into a mine below the river bed (ARC and Pennsylvania Department of Environmental Resources 1975). In the Upper Silesian Coal Field many miners lost their lives when the deep underground coal mine workings approached close to the top of consolidated formation, covered with highly permeable and saturated sediments. In this case, a considerable hydraulic pressure of the overlying aquifer and mixture of water with gases proved to be highly dangerous. One of such incidents is depicted in Fig.6 [10].

One of the most spectacular disasters related to mining and ground-water occurred in 1895 in the city of Most (Brux), in northern Bohemia. Here in an underground coal mine named Anna, a sudden inrush of ground-water with quicksand caused substantial land subsidence. A total of forty houses and a railroad track collapsed or were severely damaged because of the subsidence [11].

Impact of Mining on Ground-Water Quantity and Quality

The most common impact of mining on ground-water is twofold: first, in lowering ground-water levels in a considerable area adjacent to a mine due to water inflow into the mine and/or to mine dewatering; and second, by affecting the ground-water quality.

Mining operations which extend below the water table in the mined area alter the original hydrogeologic regime. Water inflow into a mine or dewatering of the mine prior to and during mining is causing a convergence of the ground-water flow toward the mine. Typically, during a long-term operation and drainage of a mine, a large cone of depression in the water table is developed around the mine. The extent of the cone of depression depends on several hydrogeologic and technical factors. In the practice of mining there are known cases where the zone of influence on ground-water levels caused by mining extended more than 10 km from the mine [12].

According to Peek [13], the operation of a single phosphate mine in the Coastal Plain of North Carolina resulted in the withdrawal of about 0.2 mio m^3 of water per day. This withdrawal caused a lowering of the water level in the artesian system by more than 1.5 m in an area of about 3,367 km^2. The effect of mine dewatering on the local water table was observed 64 km from the mine.

The development of such large zones of influence on the ground-water levels often causes a decline of water levels of drying of water supply wells, and changes the re-charge and discharge characteristics of significant aquifers.

Coal and metallic mining has seriously degraded the surface and ground-water quality in many mining areas. Acid mine drainage, a term applied to acidic water draining from active or abandoned mines, is quite severe in many coal and metallic mining areas. In the Appalachian region of the USA, about 6,000 t of sulfuric acid are produced daily through oxidation of pyrite, mostly in abandoned coal mines (Ahmad 1974).[14] [15] According to the US Bureau of Mines there are 19,000 inactive or abandoned mines in the United States affecting 10,000 km of streams and 11,740 ha of reservoirs (US Bureau of Mines) [16].

Acid mine drainage is the most common pollutant of ground-water caused by mining. However, other types of pollution such as toxic concentration of heavy metals are also of concern.

THE ROLE OF GROUND-WATER IN THE GENERATION OF LANDSLIDES

The problem of stability of both natural or man-made slopes is very common in many fields of human activities, particularly in civil engineering and mining.

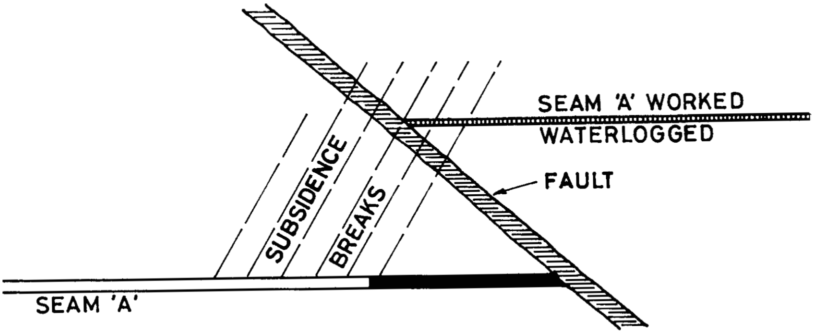

Figure 5 An example of a potential for a sudden water inflow into a mine (from Nelson, 1948)

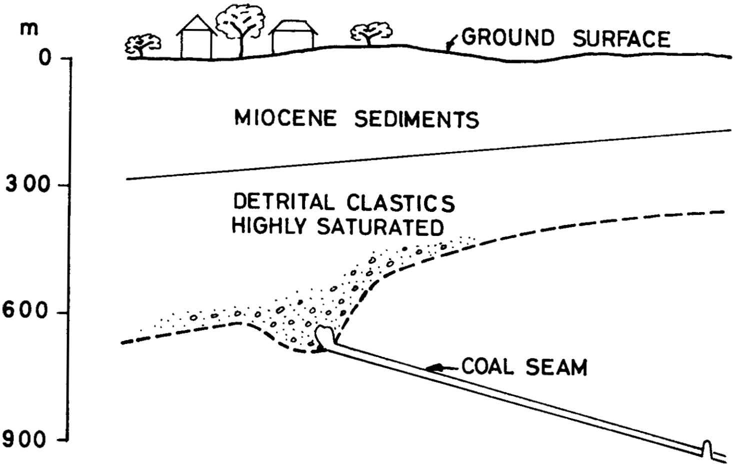

Figure 6 Sudden inrush of water into a mine after approaching highly saturated aquifer (after Straskraba, 1962)

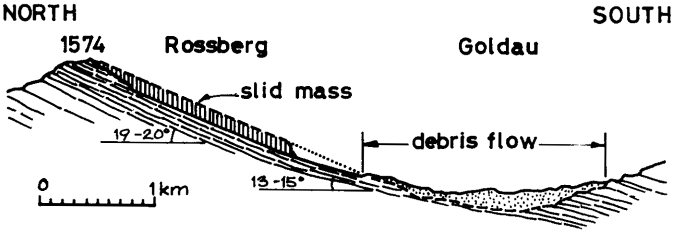

Figure 7 Slide of tertiary conglomerates along bedding planes, which in 1806 destroyed the village of Goldau in Switzerland (from Zaruba and Mencl, 1969)

Landslides are widespread in mnay countries and under varying geologic conditions. They usually cause great damages to forest growth, farmland, communication systems, engineering constructions, and buildings. There are several types of landslides (slides, falls, and flows) caused by different factors. In most cases, several factors act simultaneously, and therefore it is difficult to point out the principal factor causing the landslides. However, according to Zaruba and Mencl [17], ground-water percolating toward the surface of the slope is generally one of the most important factors.

Ground-water can affect the stability of natural and man-made slopes in several ways. First, saturation of earth materials causes a rise in pore water pressure. As the water pressure in slope materials increases, the strength of the slope decreases. Such slides generally occur during heavy rainstorms when the rate of surface infiltration exceeds the rate of deep percolation.

Removing (ashing out) fine particles of the soil or cementing materials is another way of how ground-water affects the stability of slopes. Water seeping out of the slope near the two causes softening and slake of ground masses. Many slope failures begin at the point where the water flows out of the slope.

And finally, artesian pressures in water-bearing strata can develop uplift forces on the contact of permeable and less permeable strata and originate a landslide [17].

The landslides of large volumes of soils or rocks have been experienced and referred to since Roman times. In Sqitzerland alone, there were more than 5000 people who lost their lives in landslide disasters [17]. For example, the slide of Tertiary conglomerates on the slope of Rossberg, Switzerland, in 1806 (Fig 7) destroyed the village of Goldau and took 457 lives. One of the largest landslides in the area of sensitive clays occurred near Vaerdalen, north of Trondheim in Norway in 1893. A layer of liquefied sensitive clay of a volume of 55 mil m^3 flowed down into the Vaerdalselven River valley within 30 min. The dense liquid covered an area of 8.5 km^2, destroyed 22 farms, and killed 111 people. Another landslide of considerable proportion occurred at Handlove, Czechoslovakia, in 1960. This landslide, caused by a cobmination of adverse geologic conditions, land use, and ground-water and triggered by a heavy rainfall, involved approximately 20 mio m^3 of earth material, destroyed 150 houses, and interrupted highway traffic, water-supply conduits, and power-lines [17].

Another famous example of a landslide initiated by increased water pressure by the impounded water in a reservoir caused the world's worst dam disaster at the Vaiont reservoir in Italy. On October 9, 1963, approximately 2,600 lives were lost when a huge landslide (238 mio m^3) moved down the north face of Mt. Toc, located above the reservoir, completely filled at 1.8 km section with slide material, and produced waves of water over 90 m high that swept over the dam and destroyed everything for kilometers downstream. The entire event, slide and flood, was over in less than seven minutes [18].

A description of major disasters caused by landslides could be continued at great length. However, this is beyond the scope of this paper. From the study of many landslides it is obvious that many of them could have been prevented with the command of sound knowledge of local geologic and hydrogeologic conditions.

LAND SUBSIDENCE DUE TO GROUND-WATER WITHDRAWAL

Another example of a nuisance created by ground-water, although not as drastic and spectacular as the consequences of water inflow into a mine or tunnel, is the land subsidence caused by withdrawals of ground-water.

In areas where aquifers are under confined conditions and where they consist of unconsolidated or semiconsolidated sediments, land subsidence may occur due to excessive ground-water withdrawals. The resulting reduction of artesian pressure causes an increasing load on the aquifer material, which in turn, may cause the compaction of the aquifer. Similar cases may occur in the karstic areas where sinkholes of dolinas can develop as a result of declining ground-water levels.

According to Walton [19], land subsidence of several decimeters has been recorded in the following areas of the USA: the upper Gulf coastal region, Texas; the Savannah area in Georgia; and in the Las Vegas Valley in Nevada. The largest area affected by the land subsidence is most probably the San Joaquin Valley in California. Here, in an area of more than 6,475 km^2, 0.3 m of subsidence has been observed for each 3 to 7.6 m of artesian pressure decline.

Freeze and Cherry [1] include other cases - the Wilmington oil field in Long Beach, California, and Mexico City, Mexico - where the ground-water overdrafts have led to rates of subsidence of almost 1 m every 3 years during the period 1935-1970.

Le Grand [20] reported that withdrawal of water from the deep gold mines of the Transvaal, South Africa, has accelerated the development of sinkholes in the overlying dolomite. This development has caused great property damage, the engulfment and collapse of large buildings, and the death of 29 people in 1962. According to Foose [21] pumping from a limestone quarry in the Hershey Valley of Pennsylvania in the USA caused sinkhole development in the surrounding populated area. Similar cases occurred in Florida (USA), Jugoslavia, and other countries.

CONCLUSIONS

This paper is intended to emphasize the negative aspects of the presence of ground-water and its hindrances of human efforts. Several examples, where many lives were lost and considerable expenditures incurred due to ground-water related disasters, are given in this paper. The history of mining and tunneling has shown the most spectacular cases of ground-water acting as a nuisance.

Following the occurrence and severity of ground-water related problems throughout the history of mining, tunneling, and landslides, it seems that with the development of scientific hydrogeology and increased involvement of professionals, who have gained invaluable experience from projects where ground-water related problems are anticipated, the severity of problems and occurrence of losses of human lives as well as economical losses were substantially reduced.

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