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The effects of water interactions on engineering structures

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ABSTRACT The intended performance of hydraulic structures such as dams built on soluble rock or soil foundations may depend upon rates of dissolution caused by water seeping through joints, fissures or granular zones. Previous papers by one author and collaborators have defined the rates of dissolution for soluble rocks by means of a simple equation: $dM/dt = K\ A\ (C_s - C)^{\theta}$. This relationship may be used as an aid to prediction of enlargement of joints and fissures in rocks, settlements of granular foundation strata, the deterioration of filters, risks to shallow but intensely loaded foundations, and durability of underground storage caverns in soluble rocks. The relationship requires a knowledge of the solution potentials of groundwater associated with these features of engineering structures. They in turn require an understanding of the relevant hydrochemistry and hydrology which is discussed in this paper.

Effets des interactions de l'eau sur les ouvrages hydrauliques

RESUME Le comportement que l'on avait prévu pour des ouvrages hydrauliques tels que les barrages construits sur de la roche soluble ou des fondations en terre peut répondre ou non aux prévisions suivant les taux de dissolution résultant de l'eau s'infiltrant à travers les joints, les fissures ou les zones granulaires. Des études précédentes effectuées par un auteur et ses collaborateurs ont déterminé les taux de dissolution des roches solubles au moyen d'une équation simple: $dM/dt = K\ A\ (C_s - C)^{\theta}$. On peut s'aider de cette relation pour prédire l'agrandissement des joints et des fissures se produisant dans les roches, les tassements des strates de fondations granulaires, la détérioration des filtres, les risques encourus par des fondations peu profondes supportant toutefois des charges excessives et la durabilité des cavernes de stockage souterraines creusées dans des roches solubles. La relation exige une connaissance de la capacité de dissolution des eaux souterraines, associée aux particularités propres aux ouvrages de génie civil. Ceux-ci, à leur tour, exigent la compréhension de l'hydrologie appropriées dont on fait mention dans cette étude.

ENGINEERING PROBLEMS

The interactions of water with soil and rock are important to many engineering structures built to contain or transport water. They can affect certain types of long-term underground storage facilities and intensely loaded foundations of large structures. Some engineering problems of soluble rocks have been discussed at a symposium at Istanbul (Anon, 1981) and at a conference at Cardiff (Anon, 1977).

James & Lupton (1978), James & Kirkpatrick (1980) and James *et al.* (1981) describe a quantitative theory for the dissolution of soluble rocks as an aid to the design of safe and durable structures but without describing the relevant hydrochemistry. Recent experience with real structures has underlined the need for a systematic approach to this aspect of the problem.

Dams

Seepage through the foundations and abutments of dams containing soluble rocks may produce settlements and redistribution of pore pressures which could threaten stability or cause leakage and waste of water sufficient to render the dam uneconomic. Dissolution of the fine fractions of filters may make them inoperative and threaten the safety of the dam.

Underground storage caverns

The storage of radioactive waste in massive salt strata has been discussed by Albrecht *et al.* (1980) and consideration has been given to storage in disused anhydrite mines (Fullalove, 1983). Long-term security of such storage caverns can be affected by the ingress of water the composition of which affects both solubility and the specific rates of dissolution of anhydrite.

Foundations for heavily loaded structures

Intensely loaded foundations on soluble soils are also vulnerable (e.g. Anon, 1983) when only very small settlements can be tolerated. Such problems have been met in Iraq in relatively shallow gypsiferous soil with a fluctuating water table.

Geological phenomena

Occasionally an active dissolution process can be observed, for example the creation of caves or the erosion of cliffs by a river. A gypsum cliff beside the River Ure at Ripon Parks in Yorkshire, England, was investigated by James *et al.* (1981) to show that the cliff was retreating at a rate of about 0.1 m year^{-1}.

THEORETICAL CONSIDERATIONS

James *et al.* (1978, 1980 & 1981) established the relationship for dissolution of soluble rocks as:

$$\frac{dM}{dt} = K\ A\ (C_s - C)^{\theta} \qquad (1)$$

where K is the dissolution rate constant, C_s is the solubility of the rock in the seeping water, and C the instantaneous concentration of dissolved rock component in water flowing over an area A; θ has the value of 2 for anhydrite and 1 for calcareous rock, gypsum and halite. The effect of flow velocity and temperature upon the value of K was also described.

Equation (1) may be used to describe the rate and manner of enlargement of fissures (Fig.1). Figure 2 describes a theoretical model from which may be derived:

$$\frac{C_1 - C_o}{C_s - C_o} = 1 - e^{-2KL/v\omega} \qquad (2)$$

where

C_o is the natural concentration of soluble rock in the groundwater;

C_1 is the concentration at distance L from the inlet to the fissure;

C_s is the concentration of groundwater saturated with the soluble rock;

ω is the width of the fissure;

K is the hydraulic conductivity; and

v is the flow velocity.

Also $v = g\omega^2 i/12\nu$ where ν is the kinematic viscosity and i is the average hydraulic gradient along the fissure. $C_s - C_o$ is then the

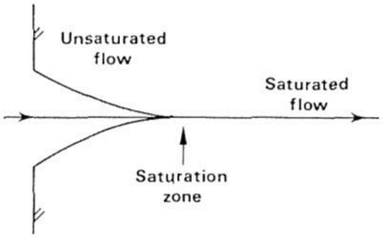

Fig. 1 Enlargement of a fissure by flow of aggressive water.

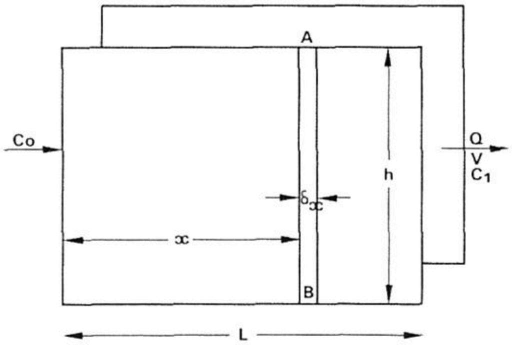

Fig. 2 A theoretical model for calculation of rate of dissolution from walls of fissure.

solution potential and therefore $(C_1 - C_o)/(C_s - C_o)$ is the degree of saturation of groundwater at a distance L from the inlet.

Equation (2) may be used to predict the type of fissure enlargement. Predictions may also be made of the rate of fissure enlargement by numerical methods. Figure 3 is a summary of the changes which occur in a fissure as "aggressive" water (unsaturated with calcium carbonate) flows through it. In Fig.3 β is the proportion of calcium carbonate in the material forming the walls of the fissure; Q_o is the initial flow rate through the fissure; and Q is the flow rate after a given period of time. Therefore Q/Q_o represents the proportional increase in flow rate.

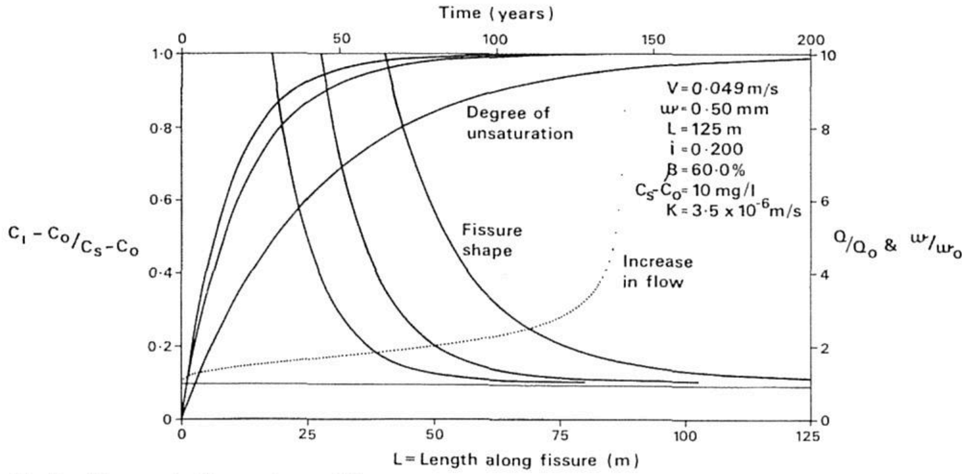

Fig. 3 Changes in fissure size and flow rate.

Degree of saturation The set of three curves in Fig.3 describe the changes in saturation level as water flows along a fissure. It becomes more saturated the further it travels, i.e. $(C_1 - C_o)/(C_s - C_o)$ approaches unity with increasing distance travelled. The three curves represent different periods of flow; the lower curve is the longest history.

Fissure shape A further set of three curves in Fig.3 shows enlargement of the fissure after increasing periods of time of flow. The wide fissures to the left of the graph represent the "trumpet" shaped enlargements at the inlet to the fissures (Fig.1) and their progress downstream as the period of flow increases.

Increase in flow The flow rate through the fissure increases with time as the fissure enlarges. The example in Fig.3 shows that flow rates accelerate sharply after about 135 years, coinciding with unsaturated water escaping from the fissure, i.e. $(C_1 - C_o)/(C_s - C_o) \to 1.0$.

Figure 4 shows the influence of solution potential, $(C_s - C_o)$, of inflowing water upon relatively small flow rates through a fissure; a relatively small increase leads to a more rapid onset of accelerating flow rates. In one case flow rates accelerate within

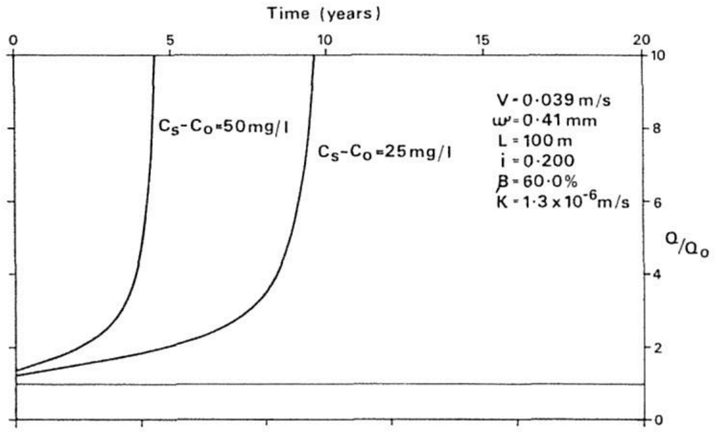

Fig. 4 Effect of solution potential on changes in flow rates through fissure.

about five years and in the other within 10 years.

Dissolution of soluble components from granular strata

Analytical solutions are available for the dissolution of granular soluble soils (James & Lupton, 1978). The lengths of the dissolution zone and its rate of growth downstream can be calculated from the permeability and approximate granulometry of the soil and the solution potential of the inflowing water.

The removal of fine particles from granular filters

Similar relationships predict changes in particle size distributions of filter material. Figure 5 illustrates theoretical changes in particle size distributions and porosity as the bed dissolves under the influence of flowing aggressive water. The filter becomes finer and at some stage suffers partial collapse as porosity increases from the original 30%.

HYDROCHEMICAL REGIMES

The natural evolution of groundwater quality between recharge and ultimate discharge has been documented for several *thick extensive formations* (Plummer, 1977; Back, 1966). It is a function of rate of movement, accessibility of reactive matter, and rate of onset of anaerobic conditions. Groundwater movement is usually sufficiently slow for rock and water to be in chemical equilibrium except in the immediate recharge area. The superimposition of a new hydrodynamic system, such as the operation of a large reservoir, of drainage works, or of high-rate groundwater pumping, may have a small regional effect, but local effects may be substantial.

Localized flow velocities, for example in fissures or permeable strata, may greatly increase. The construction of a large dam and reservoir on calcareous strata can bring water which may be unsaturated with calcium carbonate and under a substantial hydrostatic head into contact with previously dry strata. Changes in the composition of pore-fluids in contact with clay minerals can lead to changes in permeability (Hardcastle & Mitchell, 1976).

The quality of groundwater flowing around a dam structure is initially a long-term average of river water input, modified by introduced sediments, biological deposits, and thermal stratification. Filling of the reservoir may leach soluble minerals and gases from the soil and have a large short-term effect upon infiltrating water and groundwater quality. While fine sediment accumulation will help seal the reservoir, even a permeability as low as 10^{-8} m s^{-1} under 20 m head can allow leakage of 20 000 m^3 day^{-1}. Intergranular or very-fine fissure flow will inevitably develop and increase under the applied head. Soluble soil or rock strata containing carbonates, anhydrite, gypsum or halite will be vulnerable to these conditions.

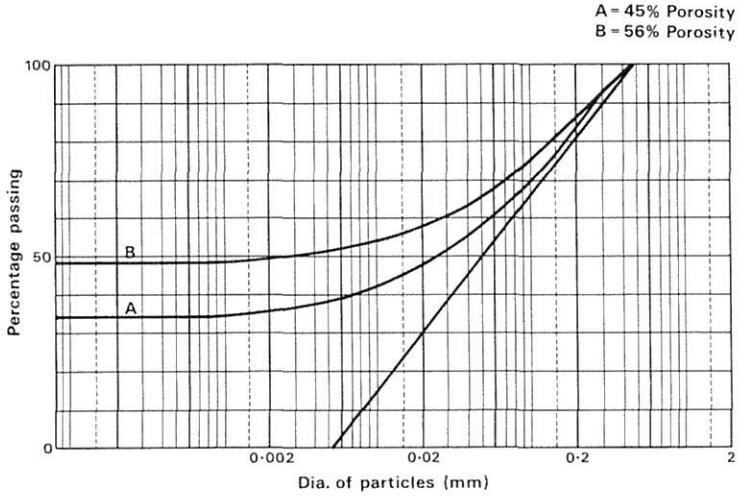

Fig. 5 Changes in the particle size distribution of dissolving granular filter material.

In relatively *thin superficial or alluvial strata*, usually permeable and water bearing, the physical impact of engineering works can be much larger than in regional aquifers. Small storage capacity allows less dilution in the event of pollution and less attenuation of water-level changes. Schwille (1976) has described the effects of a weir on the River Moselle. The thin alluvial aquifer in continuity with the river became confined, anaerobic and unsuitable for public supply. Thin silica sand/gravel aquifers are efficient transporters of aggressive water and may require special attention.

The influence of recharge, drainage and evaporation in *superficial aquifers*, where the water table is shallow, is normally large and direct and often directly measurable as a fluctuation of water level or by chemical changes. Dissolution of soluble matter may be a distinct hazard where artificial drainage increases groundwater flow, particularly at times when fresh recharge has occurred and groundwater is highly undersaturated.

SAMPLING AND MONITORING

Pre-construction survey must provide an adequate understanding of the distribution of soluble soils and rocks, the local hydrogeology and groundwater quality distribution.

It should also provide information on the locations of the geological boundaries controlling flow in the system between aquifers and surface water, the extent of existing water use and areas of natural recharge. The survey must concentrate particularly in areas which will be directly beneath and adjacent to the sites where important engineering structures are to be sited. Any monitoring system must be accessible after the engineering works are complete to provide the above data.

Monitoring

Groundwater quality data, *in situ* permeabilities (and/or flow velocities), fracture or joint sizes and distributions and variations in data for piezometric levels should be obtained either regularly or continuously. A monitoring schedule should allow the effects of new structures to be assessed, and also early warning of the need for any remedial measurement on the structure itself, as well as a check on performance as it is brought into use.
Methods: Geology is established by conventional surface mapping and drilling.

Depth-specific groundwater quality data can be obtained from samples taken from boreholes or *in situ* samplers (Edworthy, 1983). Similar data can be obtained by packer testing and it is essential that chemical and hydraulic data are related as closely as possible.

The size distribution of joints in rock may also be measured by pressure tests with packers (Snow, 1969) and tracer studies may be required to establish flow velocities in fissures or karstic strata.

The hydraulic properties of both the saturated and unsaturated zones need to be determined to establish both horizontal and vertical permeabilities and whether flow is of a diffuse, intergranular type by fissures, or confined to thin highly permeable intervals. For example, Wagner *et al.* (1976) studied the relationship between groundwater quality, rainfall and geological structure for a carbonate area in Arkansas and found a distinct relationship between fracture patterns and groundwater quality distribution.

Overall changes in groundwater flow can be assessed from water level changes measured in monitoring boreholes, preferably at more than one depth in the water-bearing strata. Downhole geophysical logging of flow velocities, differential temperature and electrical conductivity can provide valuable supplementary information on the location of fractures and allow changes in groundwater flow to be followed. Similar monitoring methods are applicable in superficial aquifers, but because of comparatively rapid and wide variation, more frequent monitoring may be essential.

Chemical fluctuations in surface water are, by comparison, extremely wide and rapid. They are governed mainly by climate and geology, but also by other factors such as industrial pollution or land drainage works. Continuous quality recording over a short period is usually necessary, followed by more restricted periodic sampling, based upon established variability.

Having calculated an average reservoir water quality, sampling of the impounded water and bottom sediments may be necessary. Appropriate methods of sampling for dissolved minerals and gases have been described by Brown *et al*. (1970). Measurement of Eh, pH, dissolved oxygen and temperature profiles in a reservoir can be carried out using specialized electrodes and sensors which are available commercially. The more difficult sampling of bottom muds has been described by Emery & Dietz (1941).

HYDROCHEMICAL ANALYSES

For engineering purposes it is usually necessary to consider one or more of the four common soluble rocks - calcium/magnesium carbonates, gypsum, anhydrite or halite.

Halite

This raises few problems of hydrochemical analysis. Solubility is high and not substantially affected by small concentrations of other ions.

Gypsum and anhydrite

The solubilities of these two minerals are much affected by dissolved salts. The solubility reaches a maximum in the presence of 3.5% sodium chloride falling to lower values at higher concentrations (Posnjak, 1938); other ions such as magnesium and potassium can alter the solubilities. At the Poechos Dam Chira Piura, Peru (Paine *et al*., 1982) the solubility of gypsum in the groundwater was 0.6 g l^{-1} or 25% more than the maximum value quoted by Posnjak. This enhanced solubility is a consequence of not only high concentrations of sodium chloride but also dissolved magnesium and alkali metal sulphates and nitrates. The solution rate constants are also influenced by dissolved salts (James & Lupton, 1978).

Conversion of solid anhydrite to solid gypsum through the solution phase with potential expansion depends upon small differences in the solubilities of the two minerals. For these various reasons it is important to use accurate methods for determining groundwater compositions (APHA *et al*., 1980) and accurate direct solubility measurements in groundwater samples.

Carbonates

The solution rate constants of various calcium/magnesium carbonates in pure water or in solutions of fixed concentrations of carbon dioxide do not appear to vary greatly (James, 1981). However, Weyl (1958) *inter alia* has shown that the solubility of calcite is greatly affected by the carbon dioxide content of the water. Lowenthal & Marais (1976) calculate the solubility of calcium carbonate from pH, alkalinity, calcium content, total dissolved solids and temperature, and Picknett (1972) has shown that magnesium can affect the solubilities in a specific manner.

Accurate measurement of field pH requires care especially in water containing relatively high concentrations of free carbon dioxide. It is difficult to measure pH accurately in deep reservoirs even with special electrode systems. The pH values of water samples measured in the laboratory usually differ from those measured *in situ* because it is difficult to prevent some loss of carbon dioxide between field and laboratory.

These difficulties were highlighted during an investigation for an Australian dam where 45 groundwater samples were taken and solution potentials determined:

(a) by calculation using *in situ* pH, temperature and laboratory measurement of the other parameters;

(b) by direct measurement saturating the water with pure $CaCO_3$; and

(c) by direct measurement using the powdered Ca/Mg carbonate foundation rock.

Values obtained by method (c) were about one half of those by (b) and one quarter of those by (a).

Other work related to a limestone dam foundation in Indonesia has shown similar if less extreme discrepancies. It can be seen from Fig.4 that such large discrepancies produce important differences in the predictions.

It must also be recognized that solution potential may depend on differences between relatively large concentrations of calcium ions. For example, the Indonesian reservoir water had a calcium content of about 25 mg l^{-1} and water seeping from the dam contained about 40 mg l^{-1}. The degree of saturation of this seepage was crucial and accurate measurements of the solution potential of the reservoir water were essential. Atomic absorption spectroscopy was used to carry out 10 separate measurements of the calcium ion concentration on each sample to determine the solution potential with a standard deviation of 1 mg l^{-1} (coefficient of variation 7%).

EFFECTS OF DISSOLUTION ON DESIGN

The foregoing illustrates the types of problem which may be associated with various engineering structures built on or within soluble rocks and soils. Various kinds of preventative or remedial measures may be considered to provide satisfactory and economic designs. It may however be demonstrated that a chosen site is unsuitable.

Foundations to dams

If joints or fissures in the soluble rock abutments or foundations carry sufficient seepage flow of aggressive water, they can enlarge and flow-rates can increase unacceptably. One preventative method is to grout the joints or fissures and thereby seal the flow passages.

Soluble materials within granular foundation layers may lead to unacceptable settlements. A suitable preventative measure might be to construct a groundwater cut-off wall "upstream" through the soluble material.

Filters

Drainage filters for dams may require protection by means of an upstream sacrificial layer of the same soluble rock. It would be possible to predict the extent and granulometry of the sacrificial layer.

Storage caverns

Long-term dimensional stability and water-tightness are of paramount importance since an uncontrollable collapse could not be tolerated. Given the local hydrochemistry, prediction of the safe life of such caverns can be made probably within an order of magnitude, sufficient to judge the feasibility of the intended use.

Intensely loaded foundations

The issue which usually has to be faced is whether protection or replacement of highly stressed zones of soluble soil or rock beneath foundations is required. It may be necessary to create a groundwater cut-off around the site or a deep protective drainage system.

CONCLUSIONS

Engineering structures founded on or in soluble rock are at risk if water moving through them is unsaturated in respect to the soluble rock.

A theoretical basis for predicting the effects of dissolution of soluble rocks or soils already exists but depends, sometimes critically, upon the solution potential of the water reaching the soluble materials. Particularly at the planning stage, but also in the specification of remedial measures, consultation with hydrogeologists and hydrologists is advisable to achieve a full understanding of the groundwater flow and chemistry and of the surface/groundwater interconnections.

Chemical analysis of the water must be carried out with suitable precision. Inadequate methods can lead to misleading predictions of dissolution. It is recommended that solution potential be determined by direct methods and not calculated from standard chemical analysis.

Strategies and methods for sampling may be critical, and need to be specially considered for each type of hydrochemical regime.

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