INFLUENCE OF VERTICAL CRUSTAL MOVEMENTS ON KARST HYDRAULICS AND THE KARSTIFICATION PROCESS

VPLIV VERTIKALNIH GIBANJ ZEMELJSKE SKORJE NA HIDRAVLIKO IN PROCESE ZAKRASEVANJA

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Ewa Liszkowska & Jerzy Liszkowski: Vpliv vertikalnih gibanj zemeljske skorje na hidravliko in procese zakrasevanja

Različna gibanja zemeljske skorje so poleg klime, reliefa, litologije in strukture najpomembnejši dejavnik v kraškem okolju. Ta gibanja neposredno vplivajo na prepustnost kraških vodonosnikov in na celotno kraško hidravliko. Deloma vplivajo tudi na disperzijo in advekcijo tokov solutantov in s tem na intenzivnost raztapljanja, to je zakrasevanja. Prispevek obravnava te povezave in omogoča tudi določeno kvantificiranje. Poudarja, da vertikalna gibanja skorje vplivajo na hidrogeologijo kraških vodonosnikov v časovnem razponu od 10^1 do 20^2 let.

Ključne besede: geologija, tektonika, hidravlika, hidrologija krasa

Abstract UDC 556.34

Ewa Liszkowska & Jerzy Liszkowski: Influence of vertical crustal movements on karst hydraulics and the karstification process

Differential vertical crustal movements are, besides, climate, relief, lithology, and structure, the most important formation factor of the karst environment. They are the effect of changes of the stress-strain state of rock masses and result in changes of elevation and slope of the Earth's surface. Thus they affect directly the permeability of the karstic aquifers and the geometric, kinematic and dynamic properties of the flow field, i.e. the whole karst hydraulics. Vertical crustal movements (VCM) control partly the dispersion and advection fluxes of solutes and thus the rate of dissolution, i.e. the rate of karstification. The paper discuss the basic theoretical background of these interrelationships which allows the quantification of some of the above conclusions. It is stressed that VCM control the hydrogeology of karstic aquifers for time intervals down to tens and hundreds of years.

Key words: geology, tectonics, hydraulics, karst hydrology

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INTRODUCTION

In Poland, as in many other European countries, carbonate aquifers, many of them strongly karstified, are important sources for municipal, industrial, agricultural and domestic water supply. However, in recent decades a steady and significant decline of head in water table as well as confined karst aquifers has been observed. A preliminary study of causes of this forced "negative retention" indicated that neither decreasing recharge as the result of (frequently assumed only) reduced precipitation, nor the increase of hydraulic conductivity as the result of dissolution explains this effect. Indeed, recent VCM are probably the principal factor responsible for this effect (Liszkowska & Liszkowski 1992).

The main objective of this paper is to testify this as-yet working hypothesis only. Our purpose here is to present the basic physical relations between VCM and the physical, hydrodynamic and dispersion field parameters of karst aquifers. The paper could be read as a contribution to theoretical karstology.

BASIC PHYSICAL RELATION BETWEEN VCM AND KARST AQUIFER CHARACTERISTICS

The relation between VCM and karst aquifer characteristics is very complex. Because of this complexity we limit our consideration to the characteristics most relevant in respect to the problem solved. As relevant characteristics of karst aquifers we consider the structural characteristics of the rock mass, as these control the permeability of the aquifer, and the rates of dispersion and advection of dissolved matter as these affect directly the karstification process. Moreover, only the simplest models and analytical and semi-analytical solutions are used in this paper because, due to the low number of parameters, they are more easily understood and suitable for preliminary evaluations in one- or two-dimensional analysis of problems. That these simplifications are not oversimplifications one may check by reading the publications cited in this text.

First, remember that the most significant characteristic of natural rock masses is their secondary porosity. Such porosity is causd by tectonic stresses and includes openings along bedding planes, fissures and joints, cleavage planes, and faults. In carbonate rocks these structural planes are commonly enlarged by solution. These structural planes control, among other things, the permeability of rock masses, defined by the hydraulic conductivity K and therefore the specific discharge V and average linear velocity U of water through fissures.

For laminar flow conditions the specific discharge V of a fissure of infinite lenght and with plane - parallel sides is given by the well known "cubic law" equation (Lomize 1951):

$$V_f = -(Cb^3)\ J, \qquad (1)$$

and for a set of parallel fissures of mean spacing $\bar{S}_f$:

$$V_f = -(Cb^2 n_f)\ J \equiv (Cb^3/\bar{S}_f)\ J, \qquad (2)$$

where b is the aperture of fisures, C is a constant including viscosity and density of water, and roughness of fissure sides, n_f is the fissure porosity, and J is the pressure or hydraulic gradient.

In analogy to Darcy's law for porous media, the quantities in brackets of equations (1) and (2) are expressions of the hydraulic conductivity of fissured media. Hence:

$$K = Cb^3, \qquad (3a)$$

or

$$K = Cb^2 n_f \equiv Cb^3/\bar{S}_f. \qquad (3b)$$

Using Forchheimer's relation $U_f = V_f/n^f$ in (2), we get:

$$U_f = Cb^2 J. \qquad (4)$$

Note that the presence of a third power in equations (1), (2), (3a) and (3b) makes hydraulic conductivity and specific discharge very sensitive to the distribution of fissure apertures. In fact, from experimental results it seems likely that flow rate through a natural fracture is proportional to b to a fourth power (sic!) (Schrauf & Evans 1986).

The most relevant pecularity of karst aquifers is defined by the solubility of the rock matrix. The dissolution of the rock matrix leads to changes of the flow geometry from fissure to pipe flow. The dissolution, i.e. karstification process, may be expressed by a special case of the general dispersion/advection equation (Scheidegger 1970, Bear 1969). Asumming that the rock matrix is essentially nonporous and impermeable and the solute distribution across the fracture aperture is constant, the dissolution process (karstification) of limestones for the case of two-dimensional flow may be expressed as the sum of three fluxes: the diffusion flux I_D, the dispersion flux I_S and the (negative) advection flux I_A. Thus the dissolution rate $\delta C/\delta t$ or total solute flux I_T may be expressed by the following (very simplyfied) equation:

$$I_T = I_D + I_S - I_A. \quad (5)$$

The diffusion flux is unrelated to any structural characteristics of the karstifying rock mass. However, the disperssion flux, which is proportional to the coefficient of dispersion D_L, is directly related to structural characteristics of the rock mass:

$$I_S \ \alpha \ D_L, \quad (6)$$

where the quantity D_L is defined by (Bear 1969):

$$D_L \equiv \alpha_L \bar{U}_X. \quad (7)$$

The symbol α_L denotes the dispersivity. For fissured media Neretnieks (1983) indicated that the dispersivity is very sensitive to the fissure apertures disribution f(b). Thus by (4), (6) may be written in the form:

$$I_S \ \alpha \ f(b)\ b^2. \quad (8)$$

Also the advection flux I_A, which is proportional to the average flow velocity $\bar{U}_X$, leads by (4) to

$$I_A \ \alpha \ b^2. \quad (9)$$

Introducing (8) and (9) equation (5) may be written

$$I_T \ \alpha \ b^2\ f(b). \quad (10)$$

Now we need to find some functional relations between VCM and the above defined structural and mass transport characteristics of karst aquifers. If these are found, the hypothesis would be accepted as (at least theoretically) valid.

VCM are the external expression of changes of the stress field in the crust (lithosphere). They are rigid translational strains of large rock masses since the changes of stresses within the crust are much below the yield stress δ_0 of the rocks. Assuming that the strains are infinitesimal and homogenous it follows from the general theory of strain (Jaeger 1969) that, using polar coordinates with the pole at the Earth's center, VCM may be identified with the elongation or contraction in radial direction e_R = !ΔH!/R, where ΔH are changes of elevation and R is the Earth's radius. These are coupled with tangential (transverse) strains e_Q which for discontinous media may be identified with relative changes of fissure apertures !Δb!/L, where L is a characteristic lenght. The components of strain could satisfy the compatibility condition, which means that they are not independent. The simplest general assumption is that they are proportional, i.e.

$$!e_Q! \; \alpha \; !e_R!. \qquad (11)$$

As we are interested in finite strains the relation (11) is almost useless for our purpose. Thus we need to find a similar relation for finite homogeneous strain. To do this we may use the elementary Euler-Bernouilli theory of the deflection of beams. From this we find that also for finite strain the tangential displacements are proportional to the vertical ones and (11) becomes for a beam dissected by discontinuities and flaws:

$$\Delta b \; \alpha \; \Delta H. \qquad (12)$$

Now remember that from (1) and (3a) it follows that:

$$\Delta K \; \alpha \; (\Delta b)^3. \qquad (13)$$

$$\text{and } \Delta V \; \alpha \; (\Delta b)^3. \qquad (14)$$

and from (8), (9) and (10) that:

$$\Delta I_T \; \alpha \; (\Delta b)^2 f(\Delta b). \qquad (15)$$

Using (12) in (13), (14) and (15) leads to the proportionalities:

$$\Delta K \; \alpha \; \Delta H^3 \qquad (16)$$

$$\Delta V \; \alpha \; \Delta H^2 \qquad (17)$$

$$\Delta I_T \; \alpha \; \Delta H^2 \, f(\Delta H) \qquad (18)$$

The proportionalities (16), (17) and (18) are the semiquantitative expressions of the functional relations between VCM and structural, kinematic and mass transport characteristics of karst aquifers sought for.

SUMMARY AND CONCLUSIONS

We have indicated that there are functional relations between VCM and some relevant characteristics of karst aquifers: their structural, hydrodynamic and mass transport parameters. These parameters define the hydraulic conductivity of the rock mass, the specific discharge and average linear velocity of water and, indirectly, the head and hydraulic gradients and thus the whole karst water flow field. Moreover, we have also documented that VCM over changes of structural characteristics define the dispersion of solutes, the advective flux of solutes and hence the rate of dissolution, i. e., the rate of karstification, too. Therefore we may conclude without exaggeration that VCM affect the whole karst development.

This conclusion seems to be not very original and there is general agreement that tectonism is one of the controlling factors in the development of karstic aquifers. There is enough evidence from field observations that this conclusion is true. However, evidence from field observations refers to long-term, involving millions and tens of million years, vertical crustal movements, i. e., true tectonic or Neotectonic ones. For such long-term vertical crustal movements the changes of position (elevation) may be of the order of $10^2 + 10^3$ m and it is not surprising that they have a major influence on hydraulic potential distribution and values, flow velocities of water in karst aquifers etc. as well as on karst topography and the geometry of the subterranean karst conduit or phreatic cave networks (cf. Ford & Williams 1989). But we wish to stress that VCM affect karst hydraulic systems and the karstification process for time intervals down to tens and hundreds of years, even if the changes of elevation are of the order of $10^{-2} + 10^{-1}$ m only. We think that this conclusion, although at yet based only on very few data is new and if proven will be great significance, both theoretical and practical. Work on the experimental verification of this hypothesis is in progress.

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REFERENCES

Bear, J., 1969: Hydrodynamic dispersion.- In: de Wiest R. J. M. (ed.), Flow through porous media, chap. 4, p. 109, Academic, New York.

Ford, D. & Williams, P., 1989: Karst geomorphology and hydrology.- Unwin Hyman, London, 601 p.

Jaeger, J. C., 1969: Elasticity, fracture and flow: with engineering and geological applications.- Methuen & Co., London, 3rd ed., 268 p.

Liszkowska, E. & Liszkowski, J., 1992: On the causes of forced negative groundwater retention in carbonate aquifers.- In: Hydrogeological problems of south-west Poland, p. 79-85 (in Polish, Engl. res.), Wrocław.

Lomize, G. M., 1951: Filtratsiia v treshchinovatykh porodakh.- (See page flow throuhg jointed rock) (in Russian). Gosenergoizdat, Moscow.

Neretnieks, I., 1983: A note on fracture flow dispersion mechanisms in the ground. Water Resour. Res., 19(2) : 364-370.

Scheidegger, A. E., 1970: Theoretical Geomorphology.- Springer, Berlin, 435 p.

Schrauf, T. W. & Evans, D. D., 1986: Laboratory studies of gas glow through a single natural fissure.- Water Resour. Res., 22(7) : 1038-1050.

Snow, D. T., 1970: The frequency and apertures of fractures in rock.- Int. J. Rock Mech. Min. Sci., 7 : 23.

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Povzetek

Različna gibanja zemeljske skorje so poleg klime, reliefa, litologije in strukture najpomembnejši dejavnik v kraškem okolju. So posledica sprememb pritiskov v kamninski gmoti ter sprememb v višinah in naklonih zemeljskega površja. Ta gibanja neposredno vplivajo na prepustnost kraških vodonosnikov in na geometrijo, kinematiko in dinamiko lastnosti celotne kraške hidravlike. Deloma vplivajo tudi na disperzijo in advekcijo tokov solutantov in s tem na intenzivnost raztapljanja, to je zakrasevanja.

Prispevek obravnava temelje teoretičnih osnov teh povezav in s tem omogoča tudi določeno kvantificiranje omenjenih izsledkov. Poudarja, da vertikalna gibanja zemeljske skorje vplivajo na hidrogeologijo kraških vodonosnikov v časovnem razponu od 10^1 do približno 20^2 let.