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Vertical variations in permeability of flysch rocks in the Czechoslovak Carpathians

Some general features of permeability distribution in flysch rocks are characterized. In a greater part of flysch regions, the near-surface zone reaching (on the regional average) to the depth of about 30 – 40 m, represents the major aquifer in flysch rock massif. Regularities in vertical distribution of permeability are quantitatively documented by results of regional evaluation of data from water injection tests (water pressure tests) carried out in the Godula Member in Czechoslovakia. The evaluations give the basis for statistical predictions of permeability, hydraulic conductivity and transmissivity distribution in the studied rocks. It can be assumed that very similar regularities should be expected in other lithostratigraphic units of the Carpathian flysch.

INTRODUCTION

In spite of the fact that flysch rocks cover a major part of the territory of Slovakia and Moravia, quantitative data on hydraulic properties of these rocks are very scarce. As yet the aquifer tests data are available only from the East Slovakia (M. Zakovič, 1979; I. Bajo, 1984), while they are lacking for western part of the Czechoslovak flysch, i.e. for the area between the High Tatra Mts and south-eastern Moravia. In such regions, the data obtained from water-injection tests (water-pressure tests) carried out for engineering-geological purposes are the only source of quantitative information on hydraulic properties of rocks (W. Jawański, 1965; H. Niedzielski, 1974; J. Jetel, L. Rybářová, 1975, 1983*a*; T. Doe, J. Remer, 1980 and others). Statistical evaluation of the data provided by water-injection tests with an appropriate hydrogeological interpretation may give a clearer insight into the nature of depth variations in permeability of flysch rocks.

GENERAL REMARKS ON HYDROGEOLOGICAL FUNCTION OF FLYSCH ROCKS

The experience gained in many flysch regions (L.A. Molokov, 1959; V.F. Linecki, 1961; J. Jetel, L. Rybárová, 1975, 1983*a*, *b*; cf. also N. Oszczypko, 1961) shows that traditional interpretation of particular rock types regarding the psammitic rocks as aquifers and the pelitic rocks as aquicludes cannot be applied quite unambiguously and in absolute sense. There is no doubt that relatively high permeability of psammites is indicated by many springs located on contacts of sandstone beds with underlying shales. Yet predominantly very low intergranular permeability of flysch sandstones as compared with the decisive role of their fracture permeability markedly obscures (especially in the near-surface zone) the relation between lithology and hydrogeological function of rocks (dependance of total effective permeability on rock type). In certain circumstances, a body of shattered and fractured shales may act as aquifer in comparison with rigid non-fractured sandstones. Hydrogeological observations in many regions of the Carpathian flysch indicate that, besides plastic pelites, thick banks of non-fractured sandstones are often also the less permeable members of flysch sequences. On the other hand, the highest inflows to boreholes and galleries are often related to an alternation of rhythmically bedded thin pelitic and psammitic layers, especially when they are tectonically crushed.

In regions built of some types of flysch sandstones of high intergranular and fracture permeability, the major aquifer is related to the near-surface zone. It represents the zone of superficial disintegration of rocks along with the overlying products of weathering, more or less conform with the ground surface. The hydrogeological function of this zone is not in an unambiguous relation to the primary lithology of rocks. On hillsides, the near-surface zone can only conduct groundwater without any marked retaining capacity: when infiltration of precipitation ceases, the major aquifer, namely the near-surface zone, is gradually emptied by gravitational outflow. Weakly pronounced control of hydrogeological function by primary lithology weakers also the hydrogeological effects of geological structure as the influence of geological structure becomes less important than that of surface morphology. The share of deeper circulation of groundwater is rather small as permeability of the near-surface zone is much higher than that of deeper parts of rock massif and mean total permeability markedly decreases with depth.

The ratio of intergranular and fracture permeability is controlled not only by lithology but, above all, by depth. In tectonically undisturbed rock masses, the share of fracture permeability decreases with depth. In deeper parts of the rock massif, the openings of fractures are gradually reduced and tbe total permeability is increasingly controlled by intergranular permeability only that is in flysch sandstones usually rather low, i.e. less than 1 milidarcy (cf. V.F. Linecki, 1961; R.S. Kopystiansky, 1966, and others). Very low intergranular permeability of flysch sandstones of the Godula Member is evidenced indirectly also by the results of studies of their porosity (J. Uhmann, 1968; J. Uhmann et al., 1973).

According to our experience and to the observations of other authors, three zones of different nature of permeability can be distinguished in the flysch rocks:

1. The near-surface zone, reaching in this area down to the depth of 30 – 40 m, locally to 50 m. Intense fracturing in this zone can be assigned to the results of temperature fluctuation, the effects of ground water and the effect to decom-

pression and relaxation of rocks during the evolution of valleys along with slipping of rocks on inclined planes of discontinuity.

In our concept, the near-surface zone is much deeper than the "strongly decomposed zone" as defined by W. Jawański, K. Thiel (1979), reaching to the depth from 1 – 5 m to 10 – 15 m at the most. Besides the elevated mean permeability, the characteristic feature of the near-surface zone is a regular and distinct decrease of permeability with depth in the range of a few orders of magnitude.

On mountain ridges and hillsides built of flysch sandstones, gaping fractures of the near-surface zone locally form continuous systems of underground cavities (joint caves). Such systems considerably increase the accumulation capacity of the rock massif and enhance the recharge in its deeper-seated parts.

2. This transition zone of open fractures below the near-surface zone has a considerably lower permeability. Nevertheless, a continuous circulation of ground water is still possible here. The depth of lower limit of this zone is different, depending on the tectonic history of the area, the morphologic exposure and the lithology of rocks. As can be deduced from the data presented by L. Bober, N. Oszczypko (1964), N. Oszczypko (1966), W. Jawański (1973), H. Niedzielski (1974, 1978), J. Jetel, L. Rybářová (1975, 1983*a*, *b*), D. Małecka, W. Murzynowski (1978), A.S. Kleczkowski (1979), M. Zakovič (1980), N. Oszczypko et al. (1981) and J. Chowaniec et al. (1982), the depth of lower limit of the regular systems of open fractures allowing continuous groundwater circulation is most often not greater than 100 m (L.A. Molokov, 1959, indicated the depth od 100 – 150 m).

3. Below the transition zone, groundwater circulation is restricted to sporadically occurring solitary open fractures or to joint concentration zones of tectonic origin. The influence of these irregularly permeable discontinuities upon the total permeability of the rock massif can hardly be predicted or expressed by a general quantitative characteristic.

HYDRAULIC PARAMETERS OF THE STUDIED ROCKS

As mentioned above, the hydraulic parameters of flysch rocks in the greater part of the Czechoslovak Carpathians can be assessed only from the data of water injection tests carried out at the geotechnical investigation of the sited of planned dams. In Czechoslovakia, the first regional interpretation of such data concerned the flysch rocks of the Silesian unit in the Moravskoslezské Beskydy Mts (J. Jetel, L. Rybářová, 1975). The bulk of the interpreted data was provided by the tests carried out in sandstones and shales of the Godula Member of the Silesian unit, other data represented the Istebna Member of the same unit. Recently, preliminary studies have been carried out in the Soláň and Zlin Members of the Magura unit in other parts of the Flysch in Moravia (J. Jetel, L. Rybářová, 1983*b*). A comparison of the conditions established in the Godula Member with the measurements made in other lithostratigraphic members of the Carpathian Flysch indicates that the differences between particular members will be only quantitative whereas the nature of the regularites will be mainly the same. The quantitative interpretation of the data from the Godula Member may thus serve as an illustrative example of general conditions controlling the permeability distribution in flysch rocks.

Hydrogeological interpretation of the results of water injection tests can be based on an approximation of actual permeability value by an approximative

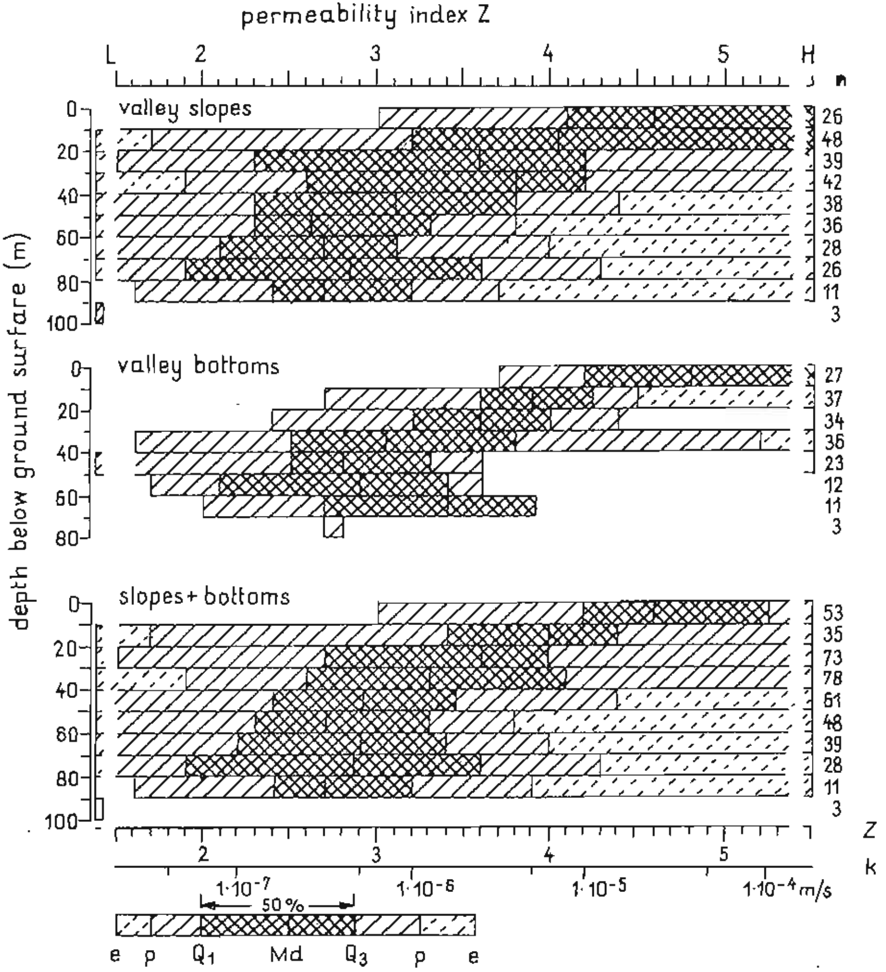


Fig. 1. Vertical distribution of permeability in the Godula Member rocks (interpretation of water injection tests — J. Jetel, L. Rybářová, 1975) expressed by frequencies of the Z-values in the depth intervals of 10 m

Pionowy rozkład przepuszczalności w skałach warstw godulskich (interpretacja próbek injekcji wody — J. Jetel, L. Rybářová, 1975) wyrażonych przez frekwencję wartości Z w interwałach co 10 m

L — too low (not measurable) values; *H* — too high (not measurable) values; *e* — extreme minimum and maximum; *p* — practical minimum and maximum; Q_1, Q_3 — first and third quartile (25 and 75%); *Md* — median

L — wartości za niskie (niemierzalne); *H* — wartości za wysokie (niemierzalne); *e* — ekstremy minimum i maximum; *p* — praktyczne minimum i maximum; Q_1, Q_3 — pierwsza i trzecia kwadryla (25 i 75%), *Md* — mediana

(comparative) logarithmic parameter — permeability index Z (J. Jetel, 1968, 1974) generally defined as

$$Z = \log(10^6 q/M) = 6 + \log(q/M) \qquad [1]$$

where: q — specific capacity (in litres per second per meter of drawdown); M — aquifer thickness (in metres). A modification of the permeability index Z has been introduced to the interpretation of the data of constant head injection tests, where instead of the specific capacity the "specific water loss" q_i has been adapted:

$$q_i = \frac{Q_i}{s_i L} \qquad [2]$$

where: Q_i – injection flowrate – in litres per second – at laminar flow, i.e. at low overpressure; s_i – the respective constant elevation of water head corresponding to the respective overpressure.

The length of tested borehole section (straddle length) L is then used instead of the aquifer thickness M, thus

$$Z = \log(10^6 q_i / L) \qquad [3]$$

Hydraulic conductivity of aquifer is generally related to the permeability index Z by the relations (J. Jetel, 1974, 1982)

$$k = \text{antilog}\,(Z + d) \cdot 10^{-9}\ \text{m/s} \qquad [4]$$

i.e.

$$k = 10^{(Z+d-9)}\text{m/s}$$

where: d – logarithmic conversion difference (J. Jetel, 1982).

In our interpretations $d = -0{,}20$ for water injection tests has been used (J. Jetel, L. Rybářová, 1975, 1983*a*). New analysis of transient flow conditions during water injection showed that in the most common conditions of injection tests an optimum approximation of hydraulic conductivity corresponds to the value of $d = -0{,}15$ (J. Jetel, 1983).

In agreement with the general regularities set forth above, more or less regular decrease of the mean permeability with depth is observed from the ground surface to the base of the near-surface zone also in the studied members of the Flysch. This decrease occurs both in the slopes and in the bottoms of valleys. Below the base of this zone only very irregular decrease of mean permeability can be observed to the depth of 90–100 m.

There is a distinct difference in permeability variation between slopes and valley bottoms. In the slopes, very high variability of permeability appears to the depth of about 50 m. With increasing depth, the difference between slopes and valley bottoms decreases. This phenomenon can be explained as a result of gravitational movements that induce significant but irregular loosening of slopes.

The vertical distribution of the values of the permeability index Z in the Godula Member (alternating sandstones and shales) is shown in Fig. 1. It is also a good example of the differences in variability between valley bottoms and slopes in particular depth intervals.

The permeability index Z is a logarithmic function of the permeability and hydraulic conductivity coefficients. The distribution of the Z-values agrees very well with the normal (Gaussian) distribution model. This fact implies thus a logarithmic-normal distribution of permeability and hydraulic conductivity.

Vertical distribution of permeability can be approximated by a model composed of several statistically homogeneous "layers" corresponding to particular horizontally stretched zones. Each of this zones (depth intervals, "layers") may be taken for a separate body, each with its own logarithmic-normal distribution of rock permeability corresponding to the normal distribution of the Z-values. The limits of individual depth intervals corresponding to the "model layers" were chosen in such a way that the best fit of the measured data with a normal model might be attained. The statistical distribution of the Z-values in particular depth intervals delimited according to this principle is shown in Fig. 2.

The mean values of permeability index Z in the Godula Member (for particular depth intervals shown in Fig. 2) can be estimated as follows:

Depth interval in meters	Number of data	Median Z	Arithmetic mean of Z	Standard error of the mean
0 – 10	53	4.6	4.70	0.70
10 – 20	84	3.9	3.88	0.88
20 – 35	111	3.7	3.46	0.97
35 – 90	227	2.9	2.90	0.88

According to the statistical evaluation of the results of water injection tests in the Godula Member also the probable ranges of individual values Z_i and actual values of arithmetic mean Z_m can be predicted for particular depth intervals (for the probability of 95%):

Depth interval im meters	Individual values Z_i	Arithmetic mean Z_m
0 – 10	3.3 – 6.1	4.51 – 4.89
10 – 20	2.1 – 5.6	3.69 – 4.07
20 – 35	1.6 – 5.4	3.28 – 3.64
35 – 90	1.2 – 4.7	2.78 – 3.02

The statistical prediction resulting from our quantitative interpretation of the data measured on the territory of Czechoslovakia agrees strikingly well with the prediction deduced from the data of the water injection tests in the Godula Member in Poland given by H. Niedzielski (1978) – after converting the data of Niedzielski to the values of Z.

Mean hydraulic conductivity for particular depth zones in the flysch rocks of the Godula Member may be predicted as follows (for $d = 0.20$):

0 – 10 m	$3 \cdot 10^{-5}$ m/s
10 – 20 m	$5 \cdot 10^{-6}$ m/s
20 – 35 m	$2 \cdot 10^{-6}$ m/s
35 – 90 m	$5 \cdot 10^{-7}$ m/s

The average hydraulic conductivity in the entire near-surface zone (0 – 35 m) with markedly regular decrease of permeability can be deduced from the median of $Z = 3.9$ (249 values) as

$$k = 5 \cdot 10^{-6} \text{ m/s}$$

The predictions given above are very near to the mean characteristics of the Magura sandstones given by N. Oszczypko et al. (1981).

The transmissivity of vertically inhomogeneous aquifer is defined as an integral:

$$T(M) = \int_{h_s}^{h_s + M} k(h) dh \qquad [5]$$

where: k – hydraulic conductivity varying with depth; h – vertical coordinate; h_s – altitude of aquifer base; M – aquifer thickness.

In a homogeneous aquifer, the transmissivity is a product

$$T = k \cdot M \qquad [6]$$

Except for some parts of valley bottoms and mountain ridges, the groundwater level fluctuates mostly in the depths from 5 to 20 m in the flysch regions. According to the equations [5] and [6] and to the mean values of hydraulic conductivity in particular depth intervals, the mean transmissivity of the near-surface zone in the Godula Member will be approximately

$$T = 2 \cdot 10^{-4}\ \mathrm{m^2/s}$$

The decisive portion of this value is represented by the transmissivity of the uppermost section of the near-surface zone (cf. Fig. 3) so that even rather small fluctuation of ground water level causes very significant change in transmissivity. High variability of the water run-off in flysch regions is hence caused just by the rapid decrease of the effective transmissivity with sinking ground water level in the near-surface zone and not by generally low permeability of flysch rocks.

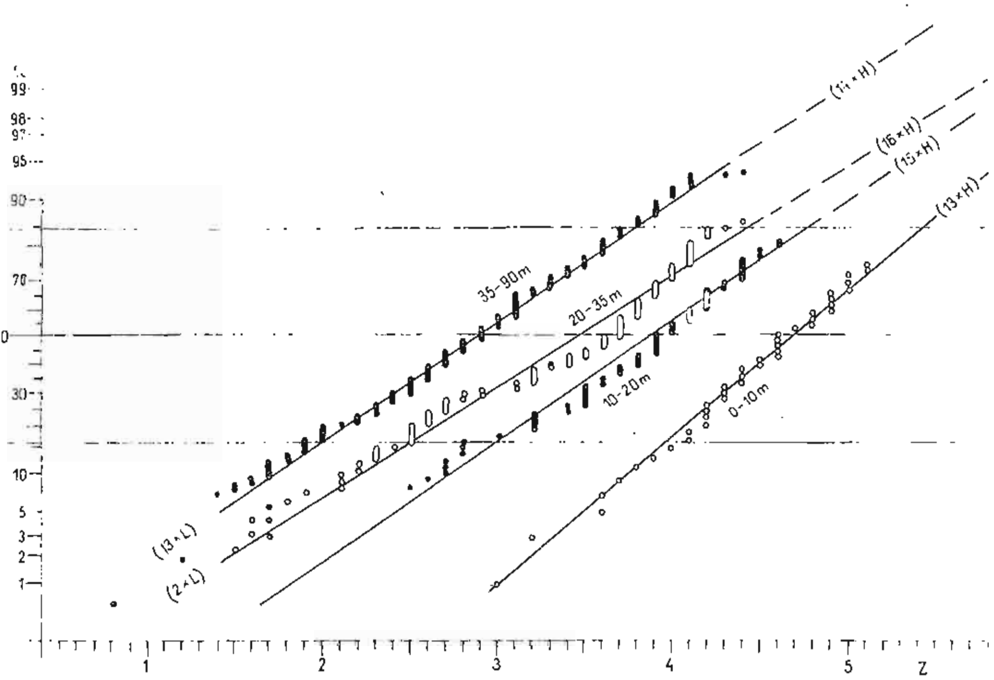
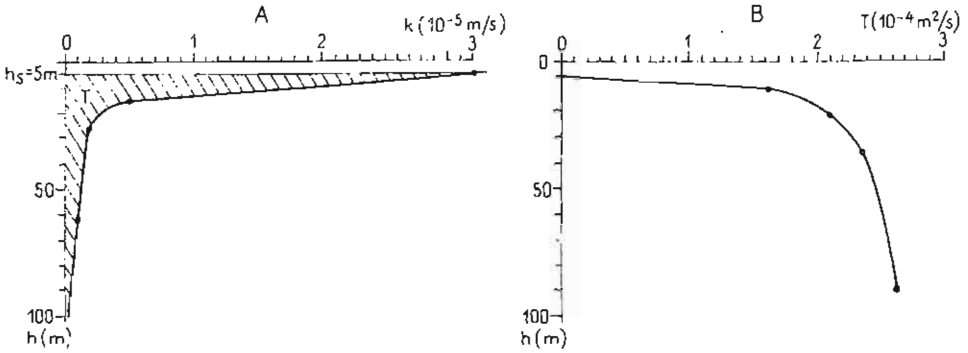


Fig. 2. Statistical distribution of permeability index Z in the rocks of the Godula Member expressed by cummulative frequency lines for particular depth intervals (J. Jetel, L. Rybářová, 1975)

Rozkład statystyczny współczynnika przepuszczalności Z w skałach warstw godulskich wyrażony przez krzywe kumulacyjne dla poszczególnych odcinków głębokościowych (J. Jetel, L. Rybářová, 1975)

$(13 \times L)$; $(14 \times H)$ – too low L and too high H values that are not measurable directly during the test

$(13 \times L)$; $(14 \times H)$ – za niskie wartości L lub za wysokie wartości H, które nie są mierzalne bezpośrednio w czasie prób



$$T(M)=\int_{h=h_s}^{h=h_s+M} k(h)\,dh$$

Fig. 3. Depth distribution of transmissivity in the Godula Member rocks
Głębokościowy rozkład przewodności w skałach warstw godulskich

A – the decrease of the mean hydraulic conductivity (*k*) with depth (*h*); the transmissivity magnitude being represented by the hatched area; B – the dependence of the transmissivity (*T*) on increasing depth (*h*); *M* – „aquifer" thickness; h_s – depth of ground water level

A – spadek średniego przewodnictwa hydraulicznego (*k*) z głębokością (*h*); wielkość przewodności przedstawia powierzchnia zakreskowana; B – zależność przewodności (*T*) od wzrostu głębokości (*h*); *M* – miąższość „wodonośca"; h_s – głębokość poziomu wody gruntowej

Considerable periodical changes in transmissivity occur predominantly in slopes and hillsides whereas in the valley bottoms the depth of ground water level is much more stable. With regard to the mean transmissivity value estimated above, there is an underestimated possibility to exploit the ground water resources in the valley bottoms of flysch regions. In the rocks of the Godula Member, the estimate of probable yield of a well 40 m deep and situated in the bottom of valley is roughly about 1 l/s (a few m³/h). Actual yields of wells in flysch rocks are, however, very variable in consequence of high hydraulic inhomogeneity of this environment (see e.g. the variability of well yields indicated by J. Chowaniec et al., 1982). Nevertheless, the statistical evaluation of the data of water injection tests can provide, in general, a good orientation not only as to the probable well yields but also as to the optimum depth of wells (cf. Fig. 3).

CONCLUSIONS

1. In the greater part of flysch regions, the near-surface zone of disintegrated and relaxed rocks function as the main aquifer. In this zone, a distinct regular decrease of mean permeability with depth can be observed on a regional scale. The mean depth of the lower limit of the near-surface zone is most often between 30 and 40 m.

2. The lower limit of the regular systems of continuous open fractures allowing more or less continuous circulation of ground water does not exceed the depth of 100 m in a majority of flysch rock massifs.

3. The data of water-injection tests (water-pressure tests) are often the only

source of quantitative information on hydraulic parameters of rocks in flysch regions. A regional statistical evaluation of this type of data with an appropriate hydrogeological interpretation can provide detailed and objective information on the regularities of vertical distribution of hydraulic properties in flysch rock masses.

4. General regularities of vertical distribution of permeability, hydraulic conductivity and transmissivity in flysch rocks have been documented by the statistical evaluation of the data provided by water injection tests in sandstones and shales of the Godula Member in Czechoslovakia. The predictions of hydraulic conductivity and transmissivity made on the base of this evaluation are very near to the mean values deduced by other authors in other lithostratigraphic members of the Carpathian flysch in Poland. The nature of vertical distribution of rock permeability and its quantitative expression seems to be very similar in various flysch regions without regard to the lithology.

5. The statistical evaluation of the data of water injection tests can serve also as a base for estimating the possible yields and the optimum depth of wells.

6. High fluctuations in surface run-off that is typical of flysch regions can be explained by specific features of permeability distribution in flysch rocks, especially by the rapid decrease of effective transmissivity with sinking ground water level.

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Ян ЕТЕЛЬ

ВЕРТИКАЛЬНАЯ ИЗМЕНЧИВОСТЬ ПРОНИЦАЕМОСТИ ФЛИШЕВЫХ ПОРОД В КАРПАТАХ ЧЕХОСЛОВАКИИ

Резюме

В статье анализируется изменчивость проницаемости с глубиной во флишевых отложениях Словакии и Морав. Отмечается, что в большинстве районов залегания флиша главной водоносной зоной являются трещиноватые и менее напряженные породы, залегающие вблизи поверхности. В этой зоне регионально можно наблюдать регулярное уменьшение проницаемости с глубиной. Средняя глубина залегания нижней границы приповерхностной трещиноватой зоны 30—40 м. Нижняя граница непрерывных систем открытых трещин, способствующих движению подземных вод, в большинстве горных массивов, состоящих из флиша, не превышает 100 м. Зачастую единственным источником колличественной информации в области гидравлических параметров пород флишевых районов являются данные о влагоемкости пород. Региональная статистическая оценка таких данных в комплексе с соответствующей гидрогеологнческой интерпретацией может дать детальную и объективную информацию о регулярности гидравлических свойств пород в вертикальном разрезе. Общая равномерность вертикального распределения проницаемости и гидравлической проводимости флишевых пород представлена статистически при оценке данных о влагоемкости пород годульских слоев в Чехословакии. Полученные данные близки к средним величинам, приводимым авторами по иным литостратиграфическим слоям карпатского флиша в Польше. Как нам кажется, сущность вертикального распределения проницаемости и ее количественные значения подобны в разных флишевых регионах, независимо от литологии. Статистическая оценка данных по влагоемкости может служить для определения потенциального дебита и оптимальной глубины буровых колодцев.

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ZMIENNOŚĆ PIONOWA PRZEPUSZCZALNOŚCI SKAŁ FLISZOWYCH W KARPATACH CZECHOSŁOWACKICH

Streszczenie

Przeanalizowano zmienność przepuszczalności z głębokością w utworach fliszowych na obszarze Słowacji i Moraw. Stwierdzono, że w większości regionów fliszowych funkcję głównego wodonośca pełni strefa przypowierzchniowa spękanych i odprężonych skał. W strefie tej, w skali regionalnej, można zaobserwować regularne zmniejszanie się średniej przepuszczalności z głębokością. Średnia głębokość dolnej granicy przypowierzchniowej strefy spękań zawiera się najczęściej w przedziale 30–40 m. Dolna granica ciągłych systemów otwartych spękań umożliwiających krążenie wód podziemnych w większości masywów zbudowanych ze skał fliszowych nie przekracza 100 m głębokości.

Jedynym źródłem ilościowej informacji w zakresie hydraulicznych parametrów skał w regionach fliszowych są często wyniki badań wodochłonności. Regionalna ocena statystyczna tego typu danych z właściwą interpretacją hydrogeologiczną może dostarczyć szczegółowej i obiektywnej informacji doty-

czącej regularności rozkładu pionowego właściwości hydraulicznych. Ogólne regularności pionowego rozkładu przepuszczalności i przewodności hydraulicznej skał fliszowych udokumentowano statystycznie, oceniając dane uzyskane podczas badań wodochłonności w warstwach godulskich w Czechosłowacji. Otrzymane wyniki są zbliżone do średnich wartości podanych przez innych autorów z odmiennych litostratygraficznie warstw fliszu karpackiego w Polsce. Wydaje się, że istota pionowego rozkładu przepuszczalności i jej ilościowe przedstawienie są bardzo zbliżone w różnych regionach fliszowych bez względu na litologię. Statystyczna ocena wyników badań wodochłonności może służyć do oceny potencjalnych wydajności i optymalnych głębokości studzien wierconych.