EVALUATION HYDROGEOLOGICAL PARAMETERS OF ROCK MASS COMPOSED OF STEEPLY DIPPING STRATA

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ABSTRACT

Rock mass composed of steeply dipping strata is drained by means of horizontal drainage wells, bored from the bottom of the open-pit. In order to evaluate the effect of drainage wells' system, i.e. to find relations between well length, distance between the wells, drawdown in rock mass aguifers, pumping rate and properties of rock mass, we used in VNIMI method of type curves' analysis. Rock mass under consideration is composed of many intermittent relatively thin layers and so has distinct anisotropy in permeability: it may be considered as aquitard across the strike of the strata whereas it is an aquifer being considered along the strike. The flow to well, bored normally to the strike, can be approximated in this case as one-dimensional flow along the strip with displaced origin of coordinates in accordance with the additional resistance connected with entrance of the flow into the well. The main formula, described such a flow is $Q=TS_o l_w \exp(-x_d^2/4at)/(\pi at)^{-0.5} = 2TS_o l_w \operatorname{expy}(y)/x_d (\pi)^{-0.5}$, where $x_d = 2h_o \ln(h_o/\pi r_w)/\pi$; x_d is the so called "displaced distance" of the coordinates' origin; $\operatorname{expy}(y)=y^{-0.5}\exp(-y)$ is the type function, using in process of type curve analysis, h_o is the depth of place of horizontal well (HW) relatively initial water level, r_w is the radius of the HW, l_w is the length of HW,S_o is the drawdown at the well, T is the transmissity of the rock mass, $T=2k\,h_o$, k is the coefficient of filtration of the rock mass along the strike of the strata, Q is the rate of discharge, t is the time; $a=k/\mu$,μ is the storage of the aquifer. Procedure of using the method of type curves' analysis is as usual except changing field data of drawdown to data of rate of discharge as a function of time. There were above 300000 m horizontal wells drilled successfully into rock mass in Kusbass coal region according VNIMI recommendations, based on rate discharge type curve analysis practically without special piezometrical observations.

INTRODUCTION

The contradiction between the conventional approach to assessment of open-pit slope stability [1,2] and the complex mechanism of open-pit slope deformations becomes apparent especially in case of steep dipping strata. The bending deformations of steeply dipping beds occur long before the ultimate equilibrium within the rock mass as a whole or even along any closed surface intersecting the beds. Prior to its final failure, the open pit slope of layered structure, when influenced by the unbalanced forces of lateral earth pressure or underground water pressure from the side of undrained rock mass, has gone through a stage of deformations initiated by the failure of cohesion along the contacts between the layers which are accompanied by bending and loosening of layers, reduction of bending rigidity, swelling of clayey partings.

One of the important negative factor, provoking unstable state of rock mass slopes composed of steeply dipping strata, is the high underground water heads which are just equal to the height of the slope due to lack of the drainage effect of the open-pit in the anisotropic rock mass excavated along the strike of the geological structure. The method of assessment of influence of underground water pressure on the slope stability, which takes into account anisotropy and tendency of strata to bending, has been described in our papers [3,4,5,6,7,8] where, based on a study of open-pit slope displacements in the Kuznetsk coal fields, analytical solutions have been obtained.

DRAINAGE TO PREVENT DEFORMATION

The only practically valuable method to prevent slope deformations is drainage of the rock mass by boring horizontal wells. Since 1984, the drainage through horizontal wells (HW) has been widely introduced in the Kuznetsk open-pit mines. To estimate the drainage efficiency, a relationship between a critical slope height (h_{cr}) and gradients of vertical filtration within the slope (i_s) and within the floor (i_f) is derived

$$h_{cr} = 3c_c / \gamma_o [(1-i_f)\tan\alpha - (1+i_s)\tan\varphi_c] \qquad (1)$$

Here c_c is the cohesion, φ_c is the angle of friction on contact planes between layers, α is the slope angle, γ_o is the specific weight of the water.

As it may be seen from this relationship, in order to prevent deformations, it is necessary that the following condition should be satisfied:

$$(1+i_s)/(1-i_f) > \tan\alpha / \tan\varphi_c \qquad (2)$$

A critical slope angle α_{cr} may be determined with regard to the drainage intensity by the following expression:

$$\tan\alpha_{cr} = [3c_c / \gamma_o h + (1+i_s)\tan\varphi_c] / (1-i_f) \qquad (3)$$

DRAINAGE IN KUZBASS

It should be mentioned that because of poor permeability of coal bearing strata across the strike, the water inflow into the open pits is formed, as a rule, for the most part by the runoff from the area of excavation and by groundwater flow through loose sedimentary rocks, in particular if there are the stable sources of recharge such as tailings ponds or rivers in the vicinity of the open-pit area. Therefore, from the practical point of view, the horizontal well drainage efficiency being estimated either in terms of total discharge of HW or according to contribution of this drainage means to reducing other components of water inflow does not offset the cost of drilling as the HW discharge is small when compared to open-pit drainage. Besides, after the mouth of the HW is destroyed due to mining operations, the well discharge is impossible to measure.

Table 1.Drilling of HW in the Kuzbass region (Dec. 1991)

Pit	HW drilled	HW retained	Total length, km	Discharge, m^3/h	Length of drained slopes, km
Kisselev	80	15	15	25	7
Vachrushev	70	5	12	60	1
Novosergeev	10	0	2	0	0.5
Krasnobrod	50	40	12	65	5
Bachat	120	40	30	50	7.5
In all	350	100	71	200	21

EVALUATION OF PARAMETERS

Beginning with the first horizontal well installed in 1975 at sliding slope in Vachrushev pit and up to 1991, method of drainage is being employed practically without checking underground water levels. Hence, the basic criterion for estimation of the drainage efficiency was the Q(t) plot for discharge Q of a horizontal well during its lifetime t from the moment of boring until destroying its mouth. For usual in mining practice lack of information about layer-by-layer characteristics of a series of strata uncovered by horizontal wells, it is advisable to select a relatively simple scheme of filtration with use of averaged filtrational parameters of rock mass and of averaged boundary conditions. Such a filtration scheme may be obtained when anisotropy of rock mass permeability and imperfection of the HW uncovering of water-bearing strata are taken into consideration and when transmissity of the HW uncovered strata is assumed constant, by analogy with the Neuman classic solution [9].So, as on account of anisotropy, the flow to the HW is considered to be close to linear, a basic relationship for the well discharge Q may be written in the following form (Fig.1):

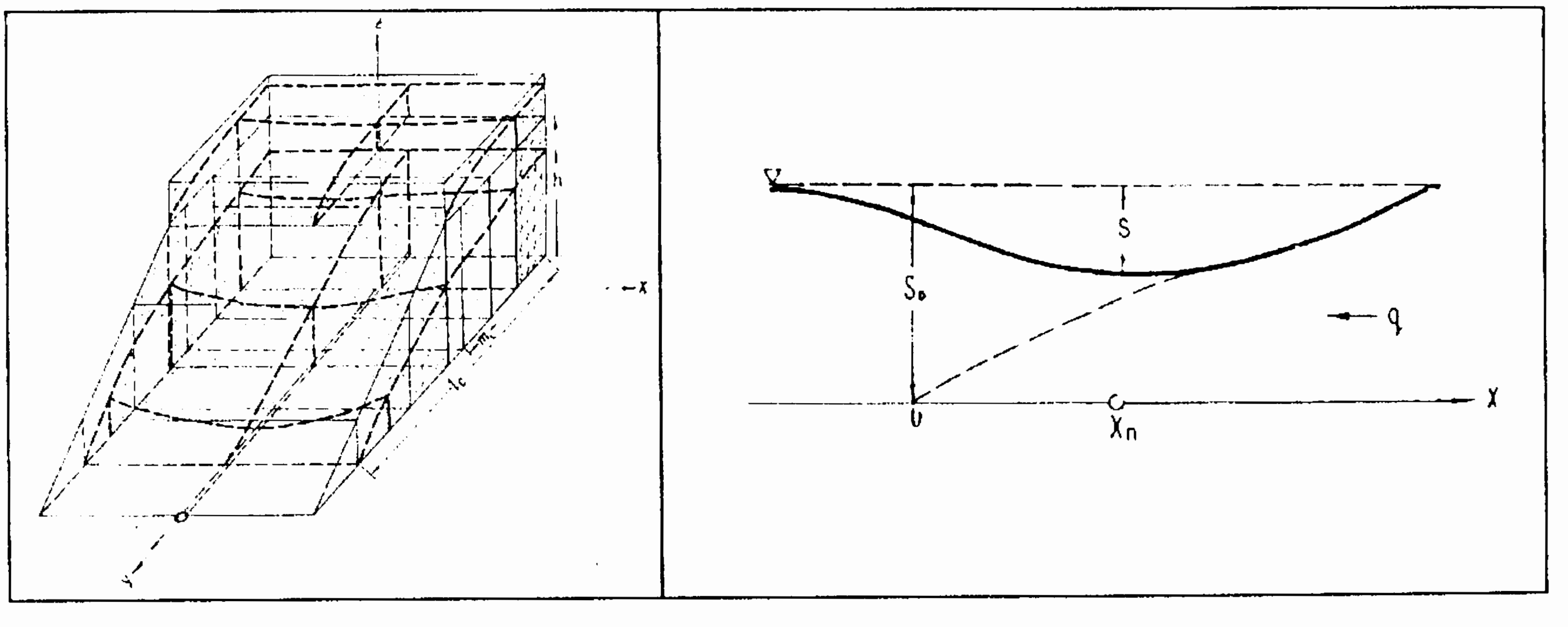

Fig.1.Flow to horizontal well.Heavy dashed lines are levels of underground water in both upper (loam) and lower (coalbearing) aquifers.

$$Q=2l_w q \quad (4)$$

$$q=TS_o \exp(-x_d^2/4at)/(\pi at)^{-0.5} \quad (5)$$

where S_o is the drawdown in the well, x_d is the conventional distance of the HW from the origin of coordinates placed in the point with drawdown S_o, T is the transmissity, $T=2kh_o$, k is coefficient of filtration along the structure, h_o is the depth of the HW relative to the bottom of loose rocks, $a=T/\mu$, μ is the storage coefficient of aquifer, $\mu=2\mu_s h_o+\mu_y$, μ_s is the specific elastic storage, μ_y is specific yield, l_w is the length of the HW.

By using the method of type curves [10], the graph Q(t) enables to obtain two relationships between T and a on the one hand and x_c on the other hand. The third missing relationship to solve a system of equations may be carried out from the solution, describing the flow to infinite chain of wells with the distance between wells $2h_o$:

$$S_o=S_l+Q\ln(h_o/\pi r_w)/2\pi T \quad (6)$$

where S_l is the drawdown in the fictitious linear flow at the well site, and r_w is the radius of the well.

By equating the value S_o-S_l from Eq.6 to an additional drawdown of the fictitious linear flow due to dismissing the well to distance x_d from the coordinates' origin, we obtain

$$x_d=(h_o/\pi)/\ln(h_o/\pi r_w) \quad (7)$$

Thus, with the thickness $2h_o$ of the zone of active water circulation, it is possible to determine the required parameters of rock mass. In order to use observation data, the function expy(y) is tabulated

$$\mathrm{expy}(y)=y^{-0.5}\exp(-y) \quad (8)$$

and expression (5) transformed into the form useful to application the type curves method, as shown in Fig.2:

$$q=2TS_o\,\mathrm{expy}(y)/x_d(\pi)^{-0.5} \quad (9)$$

where $y=x_c^2/4at$.

This solution may be used in order to evaluate the influence of neighboring HW, particularly in the most important in practice case of choosing the rational distance between the wells. The Q(t) plot shows in this case that from some moment the well discharge begins to decrease faster than it should be expected according to the Eq.(5).With dQ(t) plot made according to the type curves method the effect of interaction of horizontal wells may be estimated and the missing relationships may be obtained to refine parameters x_d, a and T and values of water table drawdown in vicinity of the HW. The situation is quite different if groundwater recharge is so significant that the period of unsteady flow is short and the HW discharge is more dependent on seasonal variations of seepage than on storage. The simplest version of the HW discharge evaluation in the case of steady flow is

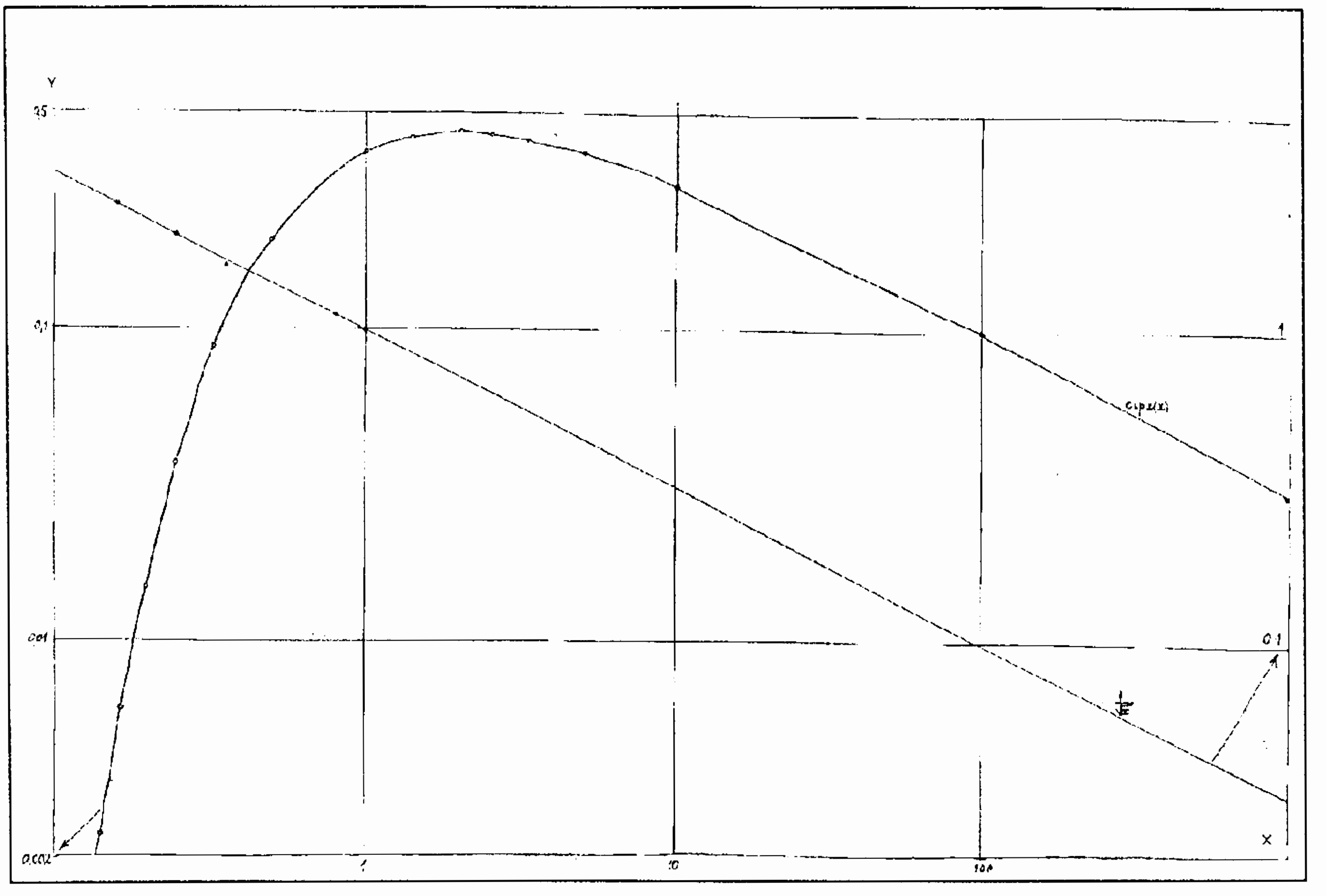

Fig.2.Type curve y=expx(x).

$$Q=wl_w L \qquad (10)$$

where w is the seepage intensity, L is the distance between the neighboring wells, l_w is the length of the HW.

While comparing the calculated value of seepage with the real value that is determined based on the precipitation-evaporation balance, it is possible to estimate an inflow rate to the open-pit wall over the aquifer of loose rocks and consider the advisability of draining this aquifer at some distance from the pit.

If the measurements of the HW discharge are carried out along with the observations of groundwater level, the assessment of the HW efficiency can be conducted with a more wide range of required quantitative characteristics of filtration process, which provides a mean for choosing the best drainage scheme. When the observations are being carried out during the period of putting the HW into service one may describe the response to the yield of linear flow at constant drawdown S_0 as follows:

$$S=S_0 \, erfc(x_{ow}^2 /4at) \qquad (11)$$

where $x_{ow} = x_d + x_w$, and x_w is a distance from the HW to the piezometer (Fig.3).

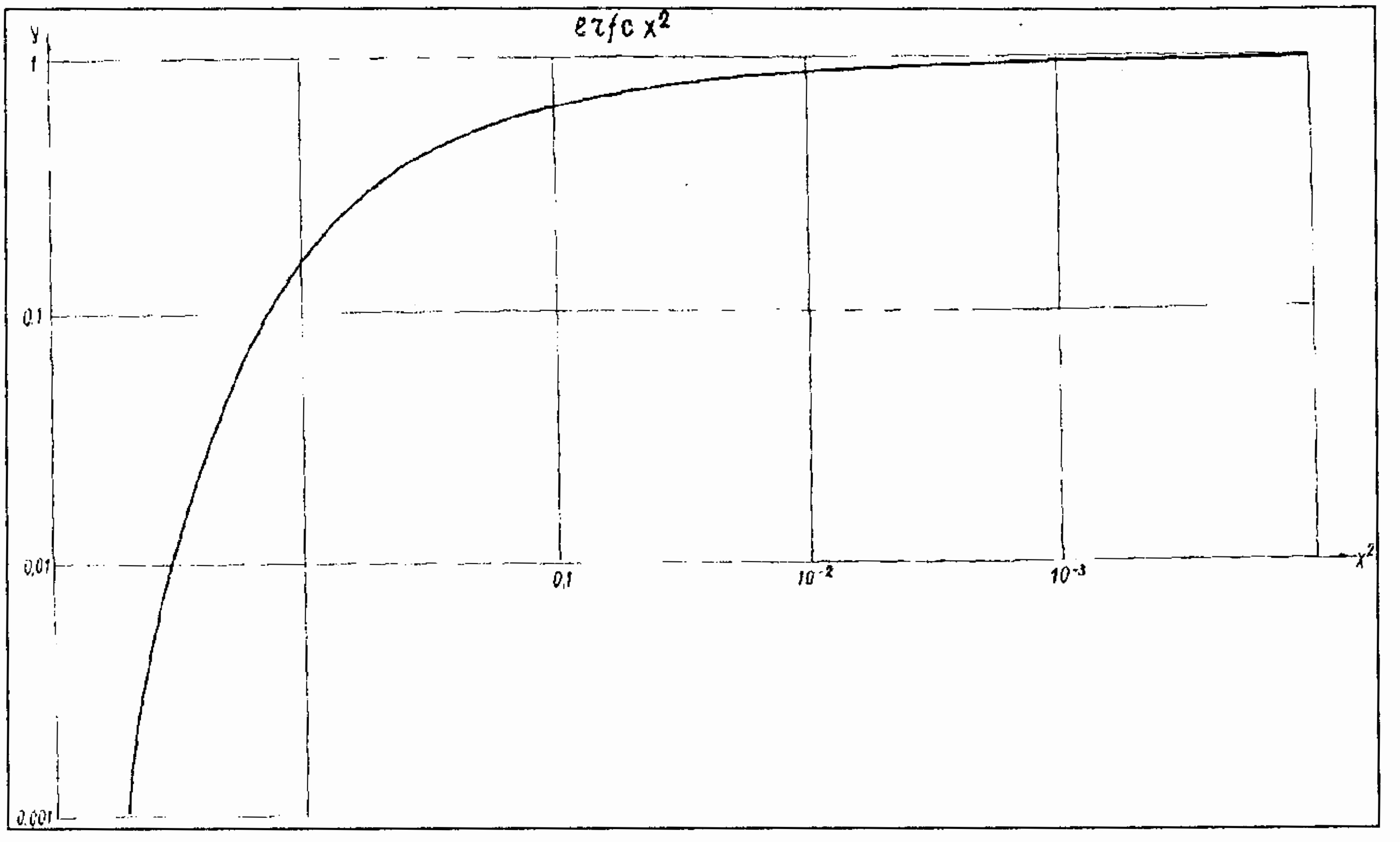

Fig.3.Type curve y=erfc(x^2).

BACHAT OPEN PIT DRAINAGE

Experience in realization of these methods for analysis of hydrogeological data may be demonstrated with the Bachat open pit [7].On the west side of this open pit there is Sagarlyc hydro-waste-disposal dump that is being covered with a pile of dry waste rock. Therefore, the problem of ensuring the stability of both the waste dump slope with a height of 110m (average dip angle of 10^o) and the open pit slope with a height between 300m (primarily) and 500m (to the limit of coal reserves) receives proper attention from the research and design team as well as from local authorities.

Horizontal wells are being used in the Bachat open pit as the drainage means since 1989. For three years 120 HW of total length 40 km had been drilled whereby about 5 km of open pit slopes had been involved. As the deepest portions of the open pit are continuously advancing the majority of these wells had been made in the upper levels at the depth of 80 to 100 metres from the earth surface. At even shallow slopes (i.e. at dip angle of 20^o to 25^o) it made possible to reach 100 metres of water saturated thickness of the floor by means of 300 m long horizontal wells. Unfortunately, the efficiency of wells began to decrease because of a small ultimate drawdown of the water table to be connected with the elevation of the HW mouth. The HW efficiency may be estimated first of all through the relationship of the wells discharge to the total inflow rate towards the open pit slopes (Table 2).

Table 2. Assessment of HW drainage efficiency in Bachat mine

1	2	3	4	5	6	7	8	9
9-west	85-89	8	8.6	1.1	0.41	0	8.6	1
4-west	38-54	13	7.2	0.5	0.13	18	25.2	0.28
9/4-west	64-75	16	10.2	0.7	0.31	20	30.2	0.33
1-east	83-90	8	10.0	1.2	0.3	15	25	0.4
2-east	46-53	11	2.5	0.2	0.08	10	12.5	0.2
9-west	79-84	10	11.7	1.2	0.6	18	29.7	0.4
In all	5 km	66	50.2	0.76	0.25	80	130	0.38

1-open-pit section, 2-profiles, 3-number of the HW, 4-total rate of the HW discharge, m^3 /h;5-average rate of the HW discharge, m^3 /h;6-specific inflow to the HW, m^2 /d;7-rate of inflow over aquifer of loose rocks, m^3 /h;8-total discharge, m^3 /h;9-coefficient of drainage efficiency by HW.

RESULTS OF DISCHARGE PLOT ANALYSIS

In some HW drilled at an early stage, the measurements of the well discharge variations at the period of unsteady flow were performed (Table 3).On a basis of Q(t) graph plotted on bylogarithmic paper by using the type curves method [10] the parameters of the uncovered strata were obtained, with the thickness of strata being treated as linear flow in strip-forming scheme. Because of the length of the HW was just the same, that is 300 metres, the main error of the calculation was introduced while assuming the value of the effective radius r_w of the HW equal to its geometrical radius (r_o =0.1m).

Table 3. Calculation of parameters based on the HW discharge

a. Pit Section No.9

1	2	3	4	5	6	7	8	9	10	11
1	5	5.2	50	140	100	80	0.63	300	0.002	0.006
2	5	2	50	180	100	145	0.87	260	0.0003	0.009
7	14	0.45	60	200	150	175	0.72	18000	0.0001	0.015
18	3.6	3.6	65	100	80	75	0.45	400	0.0001	0.006
16	9	0.6	65	100	80	75	1.1	2300	0.0005	0.014
26	20	0.9	65	100	110	85	2.8	2000	0.0014	0.025
27	15	1	70	200	110	165	2.0	7000	0.0004	0.018
28	8.5	6	70	150	100	120	1.0	600	0.0017	0.001

b. Pit Section No.4

57	6	1.4	45	300	80	240	0.48	13000	0.000036	0.006
58	30	1	50	230	100	180	5.1	8000	0.00062	0.05
59	8.5	1.2	50	230	100	180	1.4	7000	0.0002	0.014

c. Pit Section No.1

32	82	1.5	50	280	100	220	14	8000	0.0000002	0.14
36	50	0.75	50	230	100	180	8.5	12000	0.0007	0.085
37	7	1.8	50	230	100	180	1.2	8000	0.00015	0.012
42	21	3.5	50	280	100	220	3.6	3400	0.001	0.036
43	22	2.8	50	280	100	220	3.8	4300	0.0009	0.038

1-well No.; data from type curve graph: 2-Q_o, m^3 /h;3-t_o, day; 4-S_o, m; initial data: 5-length of the HW, m ;6-doubled depth of the HW horizon relatively loose rocks, 2h, m; calculated data: 7-x_d, m;8-T, m^2 /d;9-a, m^2 /d;10- storage, μ ;11-k, m/d.

As seen from Table 3, the most stable parameter, transmissity, varies between T=1-2 m^2 /d in the pit sections No.4 and No.9 and T=4-6 m^2 /d in the section No.1, with coefficient of filtration k varying from 0.01 to 0.05 m/d, respectively.

By determining the aquifer parameters on a basis of the values of the steady state inflow to the horizontal wells distributed according to the open pit sections (Table 4), we obtain lower and, evidently, more plausible parameters values for transmissity, because, in this case, it is not the data for some high-discharge wells that are taken into account but the average values of the inflow to the open-pit slope to be drained. According to Table 4, an average rate of seepage is about 0.14 of the vertical permeability, which is in a good agreement with the data of the groundwater level observations.

Table 4. Calculation of parameters in steady state conditions

1	2	3	4	5
9-west	1.1	100	0.9	0.4
4-west	0.5	80	0.4	0.2
9/4-west	0.7	70	0.6	0.5
1-east	1.2	60	1.0	0.7
2-east	0.2	50	0.2	0.14
9-east	1.2	80	1.0	0.54
In average	0.8	80	0.7	0.45

1-section No.; 2-average rate of HW discharge, m^3/h;3-drawdown at the HW, m;4-rate of seepage, mm/d;5-transmissity, m^2 /d.

GROUNDWATER LEVEL OBSERVATIONS

In 1991, three lines of piezometer wells have been drilled in the vicinity of the west wall of Bachat open pit, with three pairs of piezometers in every line. Each pair involving a 50m deep well and a 100 m deep well is located at some distance away from the crest of the upper highwall of the slope, that is between 10 and 20, 100 and 200 m, respectively. The piezometers are equipped with the filters. In the shallow wells the filters are placed in the interval near the interface between the loose rock and bedrock. In the deep piezometers the filters are installed at the site of possible maximum drainage effect in bedrock, that is near the depth of the HW installation.

As seen from the Table 5 of results of the groundwater measurements, the levels measured at the lower "stage" of piezometers, in particular in the pair of wells nearest to the pit slope, are significantly below those at the upper "stage". This fact is a consequence of the HW drainage.

Table 5. Measurement of groundwater levels in Bachat mine

1	2	3	4	5	6	7
53	240	13	13	0	-0.03	-0.03
	130	10	10	0	0.34	0.`12
	40	22	48	0.5		
80	300	2	14	0.2	0.05	0.04
	150	8	22	0.3	0.2	0.02
	10	11	50	0.55		
91	150	8	30	0.4	0.13	-0.03
	30	5	46	0.8	0.7	0.22
	-50	23	100	1.2		

1-profile No.; 2-distance from the open-pit slope; groundwater level, m:3-upper piezometer, 4-lower piezometer; filtration gradient: 5-vertical, 6-horizontal in bedrock, 7-horizontal in loose rocks aquifers.

For comparison we include the results of measurements of groundwater levels in a group wells drilled in 1979 on the profile 66 at a distance of 300 metres from the open pit (Table 6).

Table 6. Results of measurements in the wells of the group-79

1	2	3	4	5
11	130	65-130	6.9	27
1	130	65-130	6.7	-
2	205	180-205	9.7	65
4	180	140-180	9.9	-
5	130	75-130	5.3	6.5
6	65	63-65	6.7	-

1-well No.; 2-depth, m; 3-filter, m; groundwater level, m:4-08.09.79;5-11.04.92.

As it is evident from the results of measurements of groundwater level on three lines (Table 5), actual groundwater flow is a complicated process; apart from the leakage from the earth surface to the coal-bearing rocks to be drained by means of HW, there are also the pressure head gradients in the direction to the open pit fixed. The latter fact may be connected either with natural reasons such as increasing permeability in rocks in the pit slope body at account of relieving from the weight of excavated overburden and presence of flow within the aquifer in the loose rocks toward the open pit, or with purely technical reasons such as clogging the well near its bottom and progressing reduction in drainage facility of the HW from mouth to bottom.

SUMMARY

Summing up the investigations into influence of the groundwater heads on the open-pit stability in the Kuznetsk coal basin, it would be noted that the most complex and commonly encountered case is that one when the coalbearing rock mass does not include thick layers with good permeability which could be referred to in establishing a drainage system in the open pit as early as possible. Therefore, when drilling horizontal wells from the berms of the working mine it is important to organize the control for the HW discharge and observations of the groundwater levels as well as to regulate the system of water diversion from the open pit slopes and to minimize the recharge of overlying water-bearing strata within the area near the slope.

It is evident that while investigating this problem in the future, it is reasonable to rely on the approach which requires that large-scale experiments should be combined and generalized for the purpose of an adequate design scheme for drainage and deformations of open-pit slopes. Based on the thoroughly devised methodology for assessment of a role of the groundwater in stability of slopes both in non-drained open-pit slopes and the slopes with different degree of dewatering, this way enables one to avoid unforeseen complications in mining operations, with additional expenses being kept to a minimum.

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