HYDROGEOLOGICAL INVESTIGATIONS IN MINING (WITH REFERENCE TO USSR EXPERIENCE)

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ABSTRACT

The fundamental principles pursued by Soviet mining hydrogeologists are regarded and illustrated by examples from mining practice in the USSR. The logical outline of the report is as follows: 1) the effect of water on the conditions of mining operations; 2) methods to manage this effect (drainage); 3) consideration for ecological aspects of mining and drainage; 4) input information and principles of hydrogeological exploration of deposits.

It is universally recognized nowadays that the rapid increase in the average depth of mine workings leads to the vastly enhanced importance of hydrogeological factors in the economy of a mining enterprise. In the USSR it is not uncommon now that drainage accounts for as much as 10-15 and, occasionally, for 20-25 percent of the enterprise's capital expenditures (and the general scope of mining development in the USSR is quite imposing).

On the other hand, groundwater, this traditional "miner's foe", is now becoming one of the most important extractable resources. This and the deplorable ecological consequences of mining activities posed the global problem of groundwater protection and management in mining areas. It may be stated that in the USSR the general attitude to this problem as to one of paramount importance has prevented so far the critical situation characteristic for many industrially developed countries.

In dwelling on the peculiar features of Soviet experience, the extreme diversity of mining and geological conditions of developing deposits in the USSR should, indeed, be stressed. This diversity renders inexpedient certain standard approaches to drainage and groundwater protection. Hence, the emphasis which is laid on the thorough exploration of hydrogeological conditions during prospecting and the consideration they are given in designing and operating mining enterprises, i.e. on the scientific study of the problem.

EFFECT OF GROUNDWATER ON MINE WORKINGS

In this particular field of research the most notable achievements are associated with the problem of studying the role of groundwater in the stability of mine workings: it is given much consideration due to the increasing depth of mining. In the case of open workings, it concerns, first and foremost, the general and local stability of pit and spoil-bank slopes.

The largest landslides in open pits and internal dumps occur in the case of inclined bedding under the action of groundwater pressure. Such conditions are particularly characteristic for coal pits of the Urals, Siberia and the Far East. Pressured water occurs in deposits underlying coal beds which are often separated from coal by thick impervious strata. Owing to the weighing of the overburden, the friction along the contacts of sub-coal strata diminieshes drastically and deep landslides appear, involving rocks of the lying side and of internal dumps millions of cubic metres in volume. A typical instance of that kind is one of the open coal pits in the Northern Urals (Fig.1) where the pit slope 150 metres in

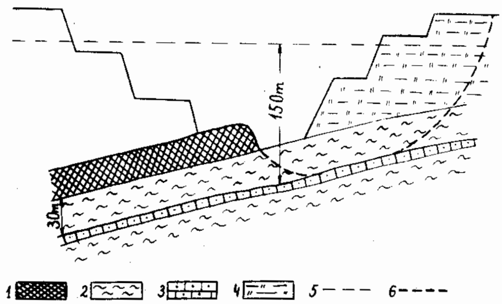

Fig.1. Scheme of landslide: 1 - coal, 2 - clay, 3 - sandstone, 4 - interval dump, 5 - piezometric level, 6 - surface of deformations.

height and the internal dumps are enveloped by a deep landslide whose base lies some 30 to 40 metres below the pit floor. The deformations were caused by pressured water occurring in the thin sandstone bands whose drainage had not been provided for by the design. Sometimes coal extraction has to be stopped for several months because of such a landslide. Particularly dramatic consequences arise from deformations in solid rocks which are due to the presence of pressured water behind impervious formations.

The danger of such deformations may affect drastically the economy of mining operations. For example, for the open coal pits of the Far East some 300 metres in depth the presence of high-pressured water reduces the admissible angle of pit slope practically by half, thus making preferable underground mining. In this way drainage of sub-coal confined aquifers becomes a major problem, for its solution is often complicated by the low permeability of rocks (coefficients of permeability are lower than 0.1-0.5 m/day).

Of similar character are landslides of external and internal dumps on a clay base, bringing about particularly grave consequences when the non-transport system of mining is employed. Such landslides are also common whenever dry spoil is dumped into old hydraulic-mine dumps (the Kuznetsk coal basin). In this case deformations are mainly caused by the developing excessive pore-water pressure in basement which consolidates very slowly. The conventional means of drainage prove to be of low efficiency in expediting the consolidation; what does help is either selective dumping (creation of a "filtering cushion") or the provision of the "sand pile" drainage.

Besides the disturbance of the general stability of the pit slope, of much significance can also be its local deformations due to seepage. An important point is that in most cases those are near-surface deformations which can be prevented not only by drainage but by less costly means as well. Such deformations may often result from some errors in mining designing, specifically, from lack of consideration for the position of contact between water-bearing and impervious layers while designing the cutting of benches. As an illustration Fig.2a shows consequences of seepage deformations in weak sandstones (Kursk Magnetic Anomaly) caused by such errors; Fig. 2b demonstrates the condition of the same section with properly cut benches, when the berm conforms to the top of an impervious layer.

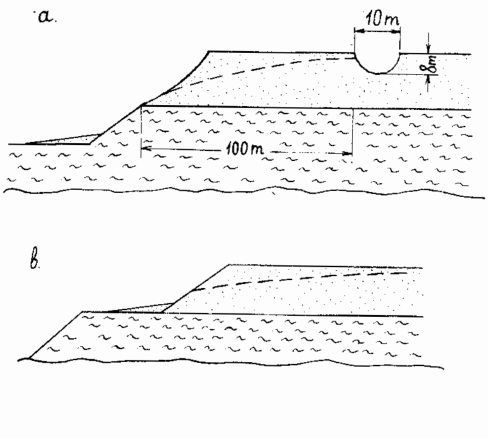

Fig.2. Scheme of seepage deformations.

As regards underground mining, I shall touch upon two problems. One concerns rock subsidence with a drastic water-level decline causing deformations of deep shafts. The reducing of hydrostatic weighing of overburden leads to the compression of rocks and longitudinal deformation of the timbering. For instance, at the Yuzhno-Belozersk iron-ore deposits the drop of head by 250 metres brought about a 3-metre subsidence of the rock mass which produced the failure of shaft timebring (about 350 metres in depth). Now, to prevent this type of deformation, provision is made in shaft designs for telescopic impervious sections.

The other problem is associated with a special method for preventing rock burst shocks by injection of water in the shock-hazardous stratum. According to this method short (about 10 m) wells are bored from the development working face (Fig. 3b) into which water is injected with a pressure of about 50 percent of overburden pressure. By creating hydrostatic weighing and enhancing the plasticity of the rock, that water produces a series of microdeformations in the rock, thereby reducing the overpressure in the vicinity of the face (Fig.3a). As a

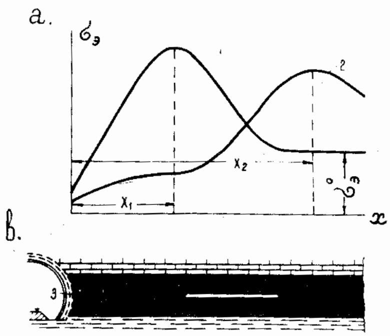

Fig.3. a. Plots of effective stresses ($\sigma_э$) before (1) and after (2) injection;
b. scheme of injection borehole (3).

result, the danger of a rock burst shock is greatly diminished. This method has proved extremely efficient at the Tkibuly brown-coal field. There is every reason to believe that it is most effective as regards shock-hazardous strata with a moderate degree of lithification.

DRAINAGE OF MINE WORKINGS

In this connection I shall deal primarily with the expedient degree of drainage. Many miners are known to adhere to the view which can be roughly expressed by the words: "pump out water wherever it occurs". Taking into consideration the expenditure involved in drainage operations, this approach is, to say the least, indiscreet. Therefore, many investigations in the USSR are aimed at answering the question: "what are the reasonable, economically expedient limits of drainage?" Let us briefly sum up the results.

In the case of open workings the extent of drainage is determined, first of all, by the necessity of ensuring the stability of rocks (indeed with due regard for the conditions of operation of mining and transport equipment and the required moisture content of the mineral). For this purpose the stability of the open-pit slope is calculated for different reduced water levels. The optimal drawdown is determined by comparing the cost of drainage with benefits as regards the volume of rocks to be excavated.

Then, a separate calculation is made for the stability of working open-pit benches. In actual practice the most common situation is that complete prevention of water inflow into the open pit is unattainable. In that case the required intensity of drainage is determined on the basis of admissible specific inflow (for one running metre of the open-pit perimeter). The magnitudes of admissible inflows, in turn, are estimated using the experimentally established values of permissible seepage deformations for different types of stripping equipment. Knowing the admissible specific inflow, the required intensity of protective drainage can be easily calculated.

Such estimates have shown that in a wide range of actual situations at pits in horizontally-lying sandy-clayey rocks the protective advanced drainage does not result in any appreciable improvement in the stability of rocks or in the conditions of operation of mining equipment. For this reason in the drainage of such rocks extensive use is now made of open water-intake equipment installed directly in the pit or of different modifications of shallow drainage. Thus, represented in Fig.4 is the scheme of mining in a thick stratum of water-

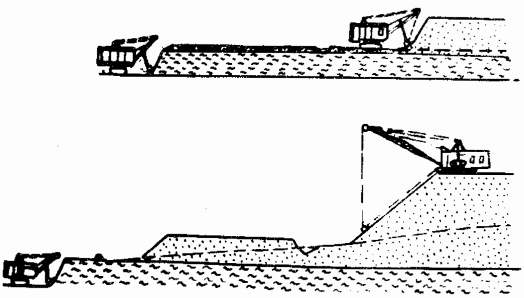

Fig.4. Schemes of mining with drainage trench.

bering sands at the base of which a small (2-4 m) layer is preserved which forms a separate bench with an underlying impermeable bed. Drainage trenches are provided in that layer, owing to which both benches are worked under "dry" conditions, without any additional drainage. Fig.5 showsthe layout of inexpensive gravity drainage of the constant side's slope by means of alongslope drainage and horizontal wells.Being most

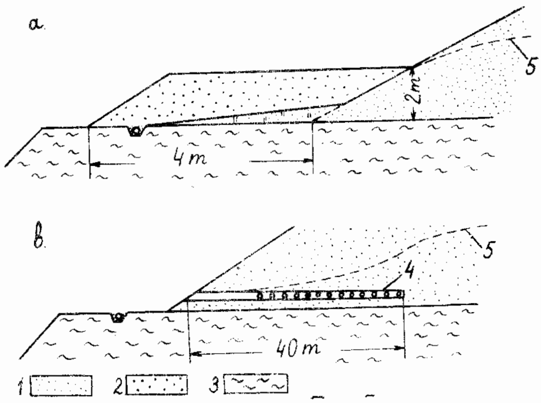

Fig.5. Schemes of alongslope drainage (a) and horizontal borehole (b): 1- sand, 2 - coarse sand, 3 - clay, 4 - borehole, 5 - water level.

closely tied in with layouts of mining operations, such systems are, in the final analysis, optimal in the technological and economic sense. Moreover, for some areas this approach to the problem of drainage made to prefer the hydraulick-mining, which proved to be more effective than the use of excavators due to the lower expenditure on drainage.

On the other hand, in the case of dipped bedding it is, as a rule, expedient to conduct preliminary deep drainage involving not only the overlying rock mass but the underlying rocks as well. In this way only the stability of the pit slopes and of the internal dumps can be ensured. In so doing,use is first made of pumping wells and then of artesian wells drilled from the open-pit bottom.

The problem of expedient drainage is particularly important in the case of underground workings under water basins or large aquifers. By the present time we have succeeded in extracting from pillars previously left under rivers, lakes or large aquifers hundreds of millions of tons of coal and other minerals. This has become possible owing to special hydrogeological investigations which proved that in the operations with a complete roof caving the water-conducting fractures do not ordinarily extend higher than the 20- to 30-fold thickness of the extracted layer. Moreover, on the basis of specialized hydrogeological observations it was possible to prove the admissibility of extracting minerals under less favourable conditions. As an example Fig.6 shows the results of observations at a site where the extracted thickness was 4-6 m, whereas the overlapping impervious layer was about 30 m thick. A series of pore-water pressure (P) transducers were installed in an impervious clay stratum. They made it possible to determine the safe upper boundary of the water-conducting fractures and, in addition, to prove the rapid restoration by clays of their impermeability properties.

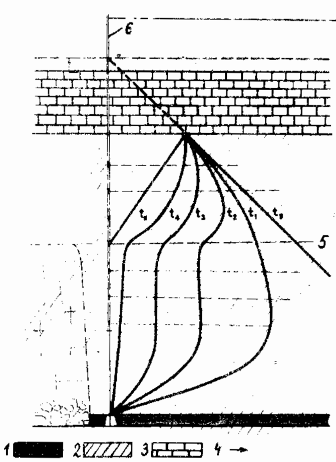

Fig.6. Pore water pressure (P) curves for different time $t_5 < t_4 < \ldots < t_0$ after undermining: 1 - ore, 2 - clay, 3 - limestone, 4 - water level, 5 - water conducting fractures (the upper level), 6 - borehole with transducers.

PROTECTION OF GROUNDWATER IN MINING AREAS

Particular attention is now being paid to the ecological consequences of mining activities which, in the hydrogeological respect, consist in the depletion and pollution of groundwater. Some legislative acts adopted in the seventies have put before the miners a series of complicated new tasks arising from the demands to take into account these two processes in the designing and operation of mining enterprises.

It is apparent that the depletion of groundwater resources is to a great extent the unavoidable result of mine drainage and water diversion. True, certain limitations in this respect are possible with a more extensive use of impermeable barrages, but the high cost of these structures at depths exceeding 20 to 40 metres prevents us from being too optimistic.

Two other possibilities appear to be much more promising:

(a) artificial replenishment of groundwater resources with pumped-out drainage water, through surface reservoirs or systems of recharging wells, which form a "water curtain" around the drained workings and thus prevent depletion of water over large areas;

(b) extensive utilization of drainage water for technological and domestic needs, i.e. its rational use permitting to work without other, special water intakes in the mining area.

The latter possibility is now rather widely and efficiently used, an account of which is given in our book "Protection of groundwater in mining areas". There are instances when the supply of drainage water for domestic purposes made it possible to satisfy the need for water of large communities, reducing prime cost of the ore by as much as 10 to 20 percent.

Clearly, such arrangements become more complicated or are altogether excluded if the pumped-out drainage water is of low quality either because of its original (natural) chemical composition or due to technogenous pollution.

From the hydrogeological point of view the former of these two cases is of fairly trivial character: the solution of the problem should be sought on the basis of using surface purification systems and utilizing pumped-out drainage water or else systems for its underground (secondary) burial (irrespective of the large cost of such systems). In such cases the economic indices of the mining activities may be affected to such an extent that those activities may prove to be altogether unprofitable (e.g.,some coal fields). The economies of other enterprises (iron ore, polymetallic, diamond mining, etc.) can stand it at the expense of raising the prime cost of the mineral product sometimes by ten to twenty percent. Generally speaking, the utilization of highly-mineralized solutions pumped out to the surface by the drainage systems of mines and open pits is for us a problem of vital importance.

Much more extensive hydrogeological investigations are required in the other case, when groundwater of initial high quality undergoes technogenous pollution in the course of developing the deposits or dressing operation. Taking into consideration that such pollution is often an unavoidable consequence of mining, it is reasonable to treat this problem as an optimization task: the admissible degree of pollution is that at which the pumped-out (specifically, drainage) water still meets certain requirements. Indeed, it is much easier to formulate this approach on paper than to accomplish it effectively in actual practice, particularly if it is remembered how limited are our possibilities of reliably forecasting pollution processes. In this connection of much advantage may be the conception of controlled pollution when the required quality of groundwater is preserved owing to: (1) processes of groundwater self-purification (sorption, ionic exchange, destruction of pollutants, etc.)[1]; (2) engineering prevention measures (aimed primarily at reducing the intensity of pollutant seepage by reliably screening the sources of pollution); (3) grondwater monitoring, i.e. specialized regime observations. On the whole, we hope to convince the miners rather soon that the protection of groundwater is not only necessary but, eventually, also economically profitable. The experience shows that elimination of advanced aquifer pollution is 10 to 100 times more expensive than its prevention, i.e. the risk in this case is almost never justified.

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1) These processes are sometimes extremely intensive; thus, we know instances of complete transformation of supersaturated brines (with mineralization exceeding 200 g/l) after their inflow in aquifer, within only 1- to 2-km interval of seepage through carbonate rocks.

ON HYDROGEOLOGICAL EXPLORATION OF MINERAL DEPOSITS

The understanding of the extreme importance of the problem of overcoming the notorious information barrier has now established itself in all earth sciences, and mining hydrogeology is not an exclusion. When we train students we accustom them to the thesis that nowadays theory is omnipotent if given the required input data. It is irrelevant to speak now of all the methodological details of this problem (yet I shall note that Soviet specialists in the past few years have accomplished a great deal both as regards the theory and methods of solving this problem). However, it might be useful to touch upon some of the fundamental principles.

Exploration of mineral deposits is a continuous multi-stage process combining surveying prior to the development of the deposit and observations in the course of construction and operation of the enterprise which are regarded as continuation of prospecting by other means. In view of the extreme importance of this observations for the efficiency of mining, it is now becoming more and more common to adopt final decisions concerning a mining enterprise design (drainage system design, in particular) only after a 2- to 3-year period of construction and operation. For this reason large mining enterprises operating under complicated hydrogeological conditions are regarded as a sort of testing sites where hydrogeological observations are conducted both for the adjustment of the mining enterprise design and for scientific generalizations. It is mostly at such testing sites (e.g. Kursk Magnetic Anomaly and Korshunovsk iron-ore field) that the abovementioned concept of controlled contamination is now being put into practice.

The foregoing presupposes a wide utilization in the hydrogeological explorations of the feedback- and successive-adaptation conceptions underlying the optimization of the exploration process. It should be pointed out that despite the apparent importance of the feedback principle, it materializes in practical explorations with great difficulties. This is due primarily to a subjective factor - the qualification of specialists. The point is that hydrogeologists engaged in the exploration of deposits are not always capable of understanding - at the computation-model level - the character of operation of the engineering structure for which explorations are conducted. If we refer again to the already quoted instance of pressured water in the open-pit bottom, it might be mentioned that quite often subcoal aquifers are left altogether beyond the framework of the exploration program due to the lack of understanding of the mechanism of the landslide process. Another instance concerns problem with the so-called "weak point", when a lot of effort and funds are expended on determining such parameters which afterwards prove to be useless for designing purposes.

There are also some difficulties in materializing the principle of adaptation, of the self-learning of explorations, although experience and model studies have shown its great efficiency. Thus, with no crude errors made at the initial stages of exploration, its efficiency increases by 30 to 50 percent due to flexible adaptation.

Among other things, a very important aspect of the "self-learning" of explorations is the understanding of their limited possibilities. Sometimes the main thing is to stop the explorations in due time and shift the bulk of expenditure on subsequent observations during the period of construction, since they may be of much more informative value. This can be illustrated by the above-mentioned cases of mining under water basins, when the mere possibility of such operations often cannot be proved on the basis of explorations.

So nowadays explorations should be regarded as a process of gradually constructing an adequate model of the explored object. In the meantime, a model, analog or digital, is becoming both a means and a goal: on the one hand, it serves as the basis for developing exploration strategy and, on the other, each new stage in prospecting provides material for the successive refining of the model. Here are some important conclusions drawn from simulation of the exploration process when various versions of hydrogeological prospecting were imitated on a digital model:

(a) The growth of exploration efficiency calls for an increasingly wide use of costly - large-scale and long-lasting - field experiments (in hydrogeology these are multiwell pumping tests) contrary to the trends towards different kinds of "express" tests. It is safe to say that most often such tests widely advertized now in the literature are a short and comparatively cheap way for determining ... erroneous input data.

(b) The sharp assymetry of the total cost curves - Fig.7

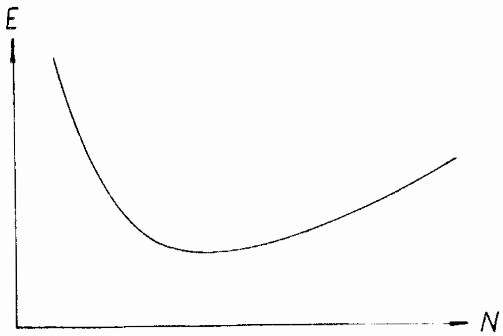

Fig.7. Typical total cost curve (results of modelling of exploration process).

(where plotted on the abscissa is the number of experiments and on the ordinate - the sum total of expenditure on exploration and risk of losses in exploatation) indicates that, economically, underexploration is much less disadvantageous than overexploration (i.e. increasing the number of experiments by 20 percent above the optimal, we risk considerably smaller sums of money than in the case of decreasing it by the same figure).

(c) On the whole, our investments in the exploration of mineral deposits are too small compared to the risk of losses in operation due to underexploration; roughly speaking, there is much truth in the statement: "cheap explorations mean expensive operation".

We shall not dwell on the important, but special problem of hydrogeological forecasting. We shall stress only one point. It does not appear very important to us which particular method - analytical, analogue or numerical - is employed in forecasting. Conversely, much emphasis is being laid on the close correlation between the mining-and-geological content of the problem at hand and its mechanical and mathematical formulation. Here lies the fundamental problem of schematizing the object under consideration, the quality of its solution determining, first and foremost, the reliability of forecasts. The understanding of this point by the rank and file specialist is, perhaps, the principal achievement of our propaganda of scientific and technical knowledge in hydrogeology. Our experience shows that this problem can be solved only by specialists well versed in each of its two aspects - mining-and-geological and mechanical-and-mathematical. It is precisely in raising the professional standards of specialists that we see one of the principal reserves for enhancing the efficiency of hydrogeological activities in mining.

We shall conclude this paper with approximately the same note that opened it. In the past decades the miners have accustomed to this stereotype: first the design of a mining enterprise is worked out and only afterwards the required hydrogeological provisions are elaborated. We believe that now this approach betokens the unsatisfactory economy of the future enterprise. At present all the main design provisions relating to the mining or dressing cycle should be most closely correlated with the requirements concerning drainage and protection of groundwater.