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Computation of and Experience on Lignite Opencast Mine Drainage

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1. INTRODUCTION

The planning of an openpit drainage represents a complex problem. Aside from hydrology and hydrogeology, the investigative phase requires the application of geology, pedology, climatology, meteorology, hydraulics of open channels, geophysics, chemistry and mathematics (statistics, theory of probabilities, modelling), including programming. In the planning stage, cost and time calculations, fluid hydraulics in pipes, soil mechanics, and the thorough knowledge of materials are added.

In an openpit drainage there is no hydrological or hydrogeological problem which does not appear in some other connection as well. On the other hand, no other problem concerning water, aside from those having to do with the drainage of mines, needs such a large number of different sciences for its solution.

No project implies the application of all the above mentioned disciplines to the same degree. Some will be used only as a secondary aid; this applies - to give you one example - to the statistical calculation of the recurrence probabilities of heavy rainfalls of the flood frequencies of rivers, if the client or government entities can provide the statistics.

The following will provide an overall idea of the individual operations which experience has shown to be the most important required in the planning of an openpit drainage, up to and including claims.

Finally, using the example of a lignite field in India, the influence of a variable geohydraulic factor - i.e. the leakage - on the drainage of an openpit will be established and the possibilities available at present for its investigation described. Since this influence can also appear in other openpit mines, it is of particular interest generally speaking.

2. CALCULATIONS AND MEASUREMENTS IN CONNECTION WITH THE PLANNING OF THE DRAINAGE OF OPENCAST COAL MINES

2.1 Ground Water affecting the Mine

Calculation of the ground water outflow at the beginning of mining operations and over the long run.
Assessment of the risk of bottom heave.

- Work involved

  Evaluation of the existing (hydro)geological data
  Determination of drilling programmes
  Core description
  Evaluation of grain-size distributions of borehole samples
  Measurements of ground water levels
  Flow measurements at springs and artesian wells
  Localization and design of pump wells and monitors
  Execution and evaluation of pump tests
  Interpretation of geophysical borehole logs and of air borne geophysics
  Interpretation of data obtained from geophysical ground methods
  Determination of water chemism

- Information obtained

  Natural directions and velocity of ground water flow

  Permeabilities, transmissivities, storage coefficients, leakage factors, drainage factors, piezometric heads, etc. of the aquifers and the overburden, coefficients of possibly impervious layers and of coal

  Hydraulic coefficients (see above) of foot wall
  Water contents and transmissivity of wash-out channels

Potential water flow from recharge boundaries (e.g. wash-out channels, permeable faults, water courses adjoining the mine)
Impact of barrier boundaries
Impact of other conditions failing to conform with the so-called ideal aquifer (anisotropy of hydraulic conductivity, sloping aquifer, wedge-shaped aquifer etc.)
Possible chemical agressivity of the ground water.

Protective Measures

Well fields for pre-drainage
Vacuum-dewatering system by well points
Slurry curtains
Drainage ditches for shallow aquifers
Relief wells in the foot wall
(Computation based on ground water models; all measures must take into consideration soil mechanical factors)
Computation of costs and of time requirements.

2.2 Surface Water affecting the Mine

Calculation of the maximum flow rates and their superposition into high-water peaks at the mine rim and within the region of the outside dumps.

- Work involved

Evaluation of climatic data and meteorological statistics
Evaluation of topographic maps
Evaluation of geological and pedologic maps
Execution and evaluation of possible further hydrological measurements
Determination of solid matter in the water, in particular during floods
Determination of the water chemism, also during floods.

- Information obtained

Size of catchment areas of the water courses crossing or touching the mine
Descending gradients of catchment areas
Roughness of ground surface (e.g. vegetation, etc.) in the river catchment areas
Branching of water courses draining the catchment areas
Dependence of precipitation on topographic height
Portion of precipitation seeping into ground
Evaporation-precipitation ratio
Run-off coefficients of catchment areas

Velocity of surface drainage
Flow velocity in the water courses
Water retention capacity of creek and river beds
Intensity, duration and percentage of occurrence of "critical precipitation"
Abrasive effects of water under normal conditions and during floods
Possible chemical agressivity of the surface water under normal conditions and during floods.

Protective Measures

Diversion canals
Protective dams
Water retention basins
River diversions
River development
Pumping stations
(Some of the computations use computer programmes; all measures must take into consideration soil mechanical factors)
Computation of costs and of time requirements.

2.3 Ground Water and Precipitation in the Mine

Computation of the precipitation representing a danger for the mine.

- Work involved

  see items 1) and 2)

- Further Calculations

  Calculation of the mine aperture and the geometry of the bottom of the mine, i.e. of the accumulated quantity of precipitation and the corresponding water level including ground water seeping into the mine
  Water from the inside dump consists of ground water and precipitation
  Determination of the maximum tolerable pump down time.

Protective Measures

Ditches on berms and benches on the inside dump and on the foot-wall
Lifting and removal of water using sump pumps and dredges
Computation of costs and of time requirements.

2.4 Possible Environmental Impact of the Mine

Active : Contamination of surface and ground water, lowering of the ground water level in the vicinity of the mine, etc.

Passive: Seepage of contaminated water or salt water - e.g. sea water - into the depression cone.

These factors are to be taken into consideration when planning the protective measures.

2.5 Possible Impairment on Existing Ground and River Water Intakes

e.g. intakes for water supply or irrigation purposes.

2.6 Expansion of Exploitation of Other Water Resources or Exploration and Development of New Resources

(applicable only when required by 2.5)

Depending on the phase in which the project is, the stress might be on different types of work. Because of the contracts to be signed individually and the conditions to which these contracts with clients must be adapted, no subdivision was made into types of study 5 to 1 or into the pre-feasibility study, feasibility study and detailed planning. -

As an example of one of the numerous problems which arise, and using for this example the lignite openpit mine in the Cuddalore Basin in India, the possible changes in leakage with time are discussed. This problem may also arise in the U.S.A. when enlarged openpit mines will be operated from the 80s onward.

3. Ground Water Leakage in a Lignite Opencast Mine in India

3.1 General Geological Data

The lignite reserves are in the south of India, in the Neyveli-Basin situated in the federal state of Tamil Nadu, approximately 17 miles from the Bay of Bengal and some 110 miles south of Madras. The opencast mine has been operated by the NEYVELI LIGNITE CORPORATION LIMITED (NLC), Neyveli, since 1957 (1).

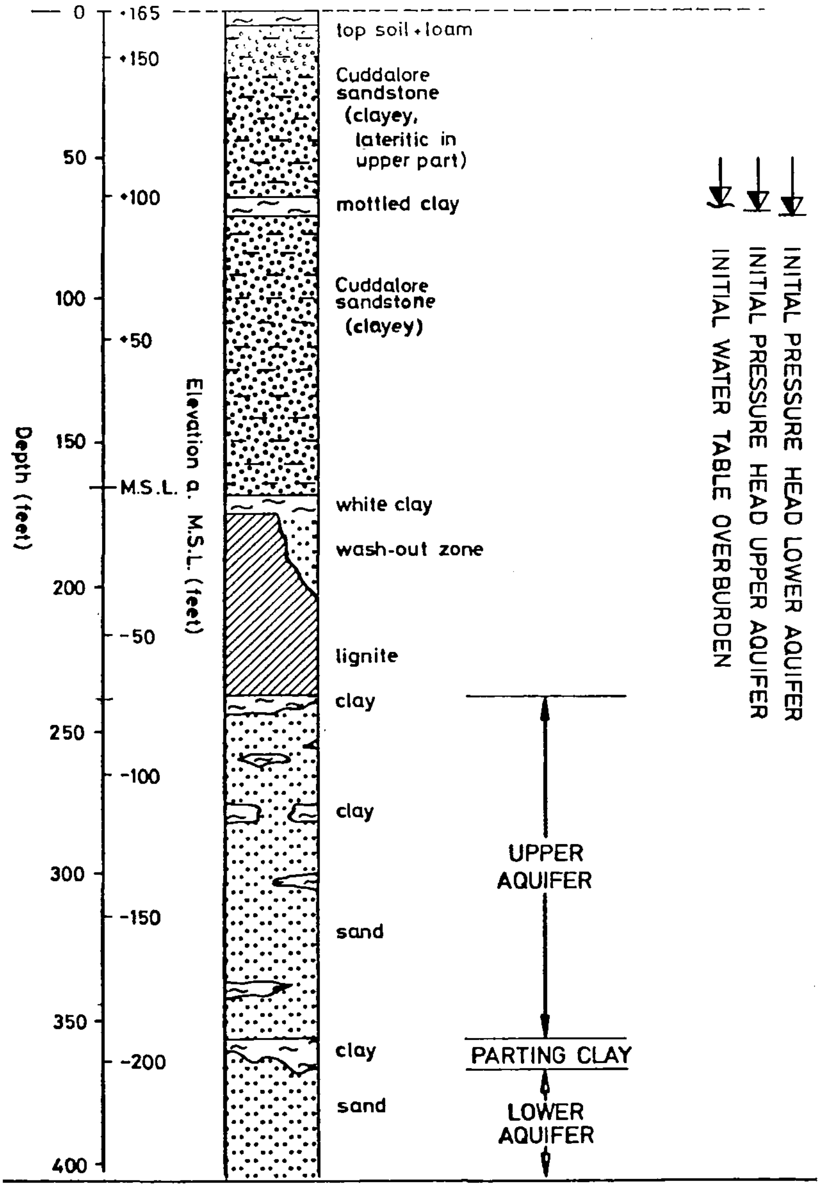

Figure 1: Neyveli Lignite Mine, Tamil Nadu, India
General Section of Strata / Pressure Head Conditions
after SUBRAMANYAM and VENKATESAN, 1969

The schematic stratigraphic log (Fig. 1) shows that below a soil layer with a thickness of about 7 feet, there are highly consolidated clayey sands down to a depth of 160 feet (Cuddalore Sandstone, Mio-Pliocene). These layers constitute the overburden. The underlying lignite seam has a thickness of approx. 50 feet. It is partly affected by washout channels which are filled with fine sand. The lignite seam is followed by a clay bed, 3 feet thick, which, however, disappears in several places. Next comes a series of beds consisting of unconsolidated sands and gravels which have been investigated by drillings to a depth of about 650 feet. These beds consist mainly of medium and coarse sands. The total thickness of the sands and gravels is unknown since there are no deep boreholes in the centre of the Cuddalore Basin. However, the deepest point is expected to have a thickness over 1100 feet. Numerous clayey lenses of varying thicknesses, some of which covering large areas, are intercalated with sands and gravels.

The ground surface of the opencast mine as well as the sequence of strata as described above incline in a south-eastern direction.

3.2 Hydrogeological Conditions

Fig. 1 shows the original pressure heads within the lignite deposit.

The overburden on top of the lignite constitutes an unconfined aquifer which is fed by precipitation and water courses.

The lignite overlies a partly interrupted clay layer under which further aquifers are encountered. There is an "upper" aquifer of some 90 feet and a considerably thicker "lower" aquifer which is likely to extend to the bottom of the basin. An intercalated clay layer reaching a thickness of approx. 8 feet on an average forms a hydraulic separation.

Both water-bearing layers are confined as they are expected to be under the prevailing geological conditions. Prior to pumping, the piezometric surface of the aquifers was approx. 160 feet above the lignite base which equals approx. 100 feet a.MSL. The phreatic surface of the unconfined aquifer is partly above and partly below the piezometric surface of the confined aquifers.

The nearest rim of the main recharge area for both aquifers is situated northwest of the mine at a distance of about 3.5 miles. Extending mostly over a somewhat higher and hilly region, the recharge area covers a southwest-northeast striking plane at least 35 miles long and 4 miles wide on an average (Fig. 2) (2).

Consistent with the dip of the layers, the ground water within all the mentioned aquifers flowed in a southeastern direction prior to pumping. However, during pumping, the equipotentials changed in such a way that the northern part of the mine receives the ground water from the north and, consequently, the western part from the west.

3.3 Ground Water Control Pattern/Calculation of Transmissivity

Lignite exploitation in deep surface mines requires extensive investigation of the hydraulic properties of all the layers involved. This must be conducted prior to and during the mining operations. In actual fact, the overburden did not need to be drained. On the other hand, the pressure head of the aquifer immediately below the lignite had to be relieved, since after the mining of lignite at the latest, the excess pressure of 160 feet would inevitably have caused a bottom heave or water outflow, thus endangering the stability of the mine slopes (Fig. 3).

When ground water control operations were started in 1961 the mine was a 5700 feet long strip. Along the two small sides and the long side opposite of the face, it was surrounded by production wells designed to drain the aquifer between the parting clay and the lignite. One "upper" and one "lower" aquifer piezometer were installed at about 1000 feet from one end of the long well row. The upper piezometer fully penetrated the aquifer, while the lower one only penetrated about 80 feet into the very thick lower aquifer. The two piezometers will again be dealt with later in this paper. These two and up to 27 other piezometers, which are situated in the surroundings of the mine, were used for the initial tests and for the execution of further calculations during the mining operations.

As the mining operations advanced, some wells within the area of the two aforementioned piezometers remained active to protect the inside dump. As for the other wells,

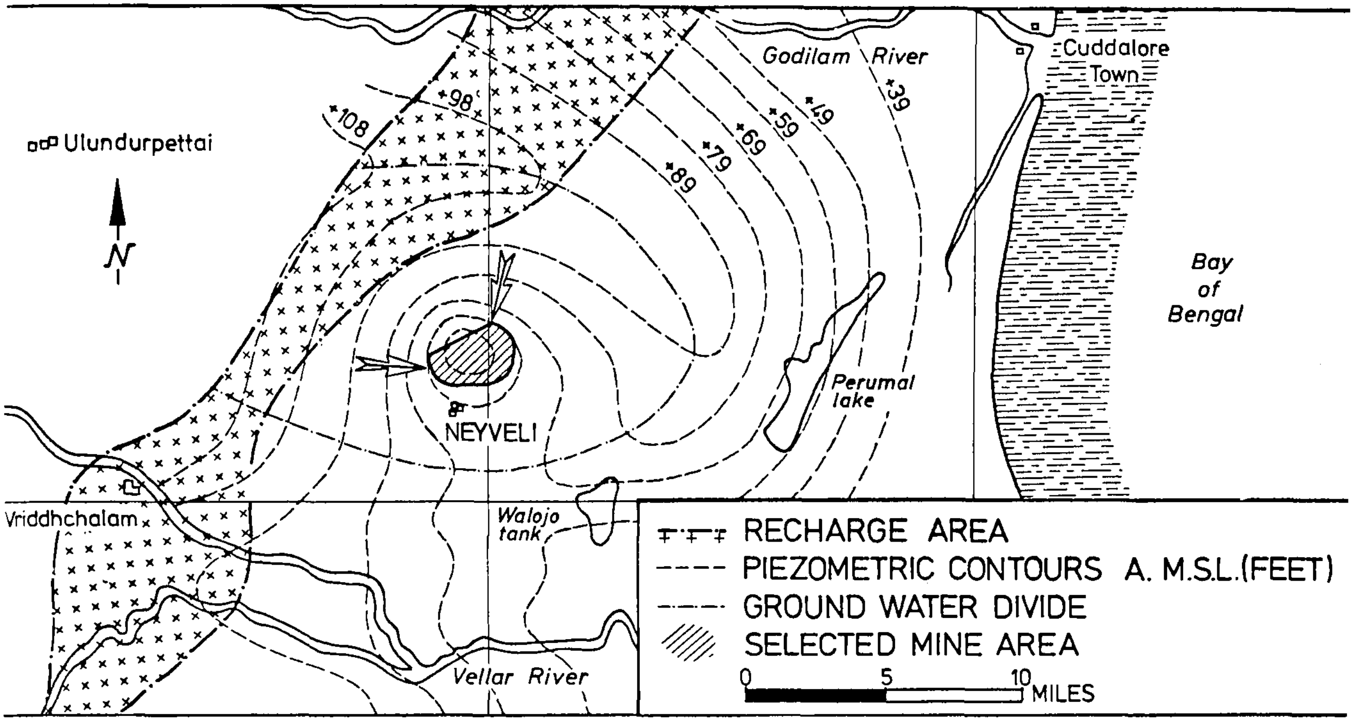

Figure 2 : PIEZOMETRIC CONTOURS UPPER AQUIFER, 1969
LIGNITE OPENCAST MINE, TAMIL NADU
NEYVELI LIGNITE CORPORATION LTD. (NLC)

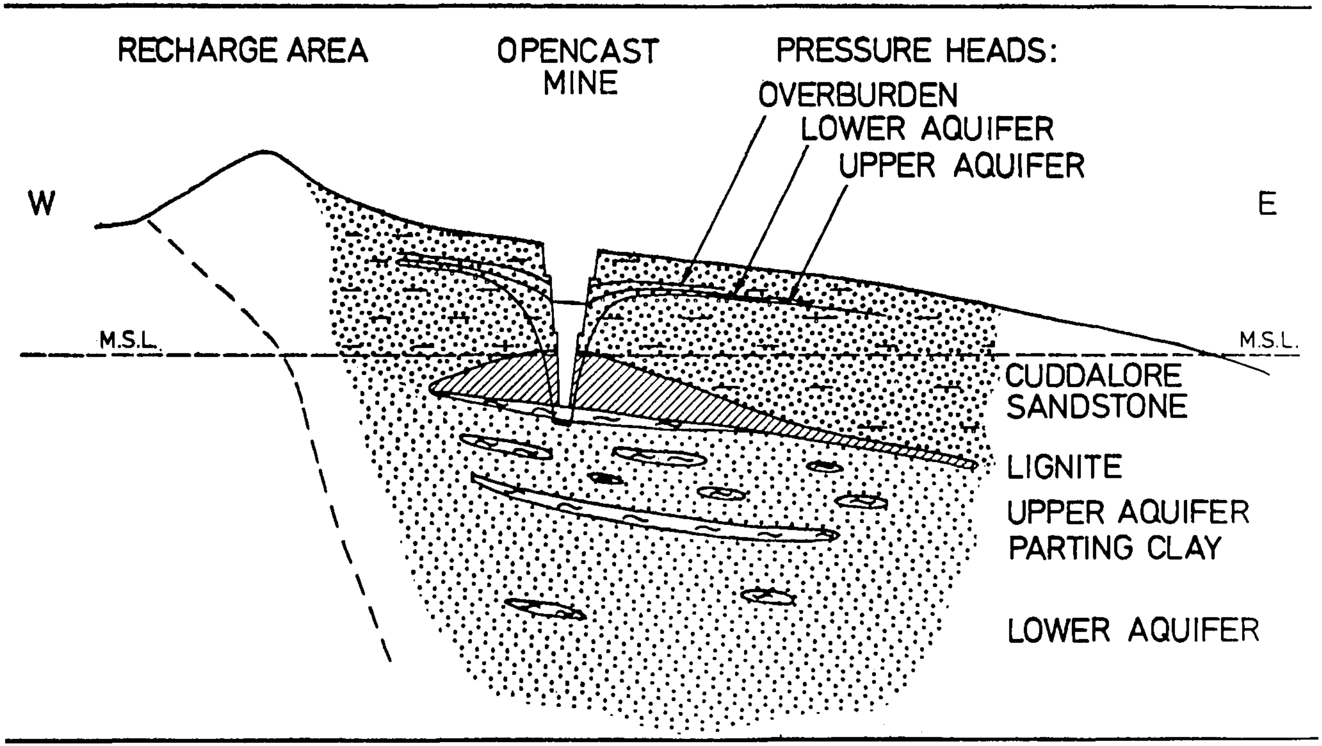

Figure 3 : SCHEMATIC CROSS SECTION OF LIGNITE DEPOSIT AND PRESENTATION OF HYDROGEOLOGICAL CONDITIONS (CUDDALORE BASIN/TAMIL NADU)

they followed the face in the array described above. This was also the reason why on the first bench of the inside dump it was necessary to sink wells.

NLC decided, as mentioned above, to relieve the pressure head only of the aquifer directly underlying the lignite. The number of active wells varied between 30 and 50; the total production ranged from 30,000 to 60,000 US gallons/minute.

The geologists of the NEYVELI LIGNITE CORPORATION (NLC) based their calculations of the transmissivity of the upper aquifer on the values obtained from the initial pump tests. Later on, they based them on the changes in the total pump rate as they occurred during the subsequent years of mining operations. They used the THIEM formula (drawdown-distance semi-log) for steady-state conditions, applying the principle of superposition (3).

In doing so, they did not consider aquifer properties that might deviate from those of the ideal aquifer. For instance, the resulting transmissivities were also marked by leakage, for it was only the upper aquifer which had to be pumped. This is also why the NLC geologists quite correctly speak of an "Apparent Transmissivity". Obviously, the almost steady-state conditions that could be observed after several weeks of pumping permitted the application of an evaluation method related to the steady-state conditions. The values thus obtained served as a basis for NLC to develop a drainage of the mine for many years.

3.4 Decrease in the "Apparent Transmissivity"

Already in the first years of pumping, the continuous evaluation of the measuring data revealed the following particularity: remaining relatively constant between 1961 and 1964, the apparent transmissivity declined steadily after this phase. While the values obtained in 1964 amounted to as much as 135,000 gallons/day/foot, the values measured in 1974 were only around 77,000 gallons/day/foot.
This decrease follows an exponential curve (Fig.4) (4).

Over the years - and as a result of a more advantageous well array -,the total pump rate of the wells could be adjusted to the empirically encountered changed conditions, i.e. it was reduced from 60,000 gallons/minute (1964) to 31,200 gallons/minute (1976). Yet, NLC realized, that a clarification and a quantitative representation of this effect

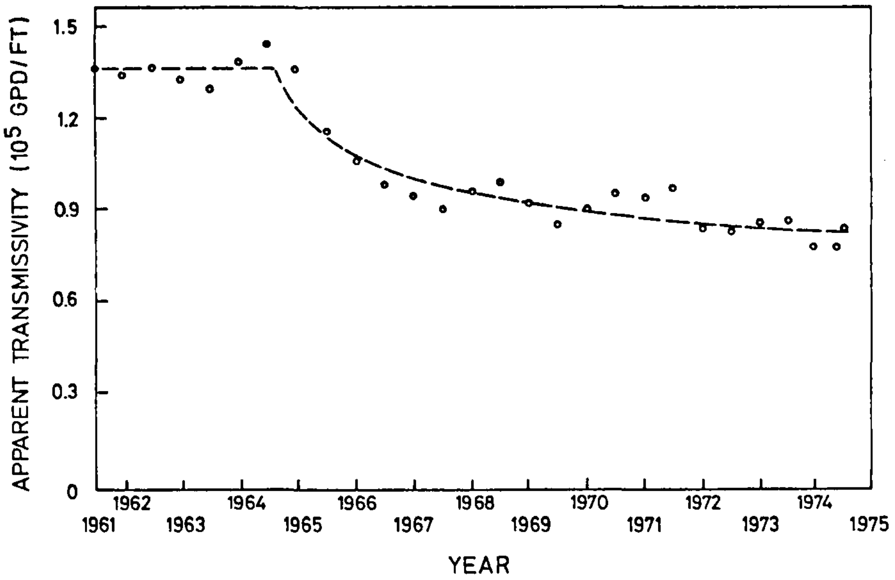

Figure 4 : TIME-VARIATION OF COMPUTED APPARENT TRANSMISSIVITIES (3 MONTH MOVING MEAN) AFTER INDIAN INSTITUTE OF TECHNOLOGY, MADRAS, 1975

would have been of advantage to allow an effective preliminary planning over several years.

3.5 Computer Models of the INDIAN INSTITUTE OF TECHNOLOGY, Madras

At the request of NLC, the HYDRAULIC ENGINEERS DEPARTMENT of the INSTITUTE OF TECHNOLOGY (IIT), Madras, then conducted a study in 1974 (4). The aim of this study was to clarify the question of whether the change in the transmissivity observed by NLC was statistically significant, whether it could be put in relation to any parameters and which drainage scheme was to be considered the most appropriate in the future.

They recalculated the drawdown curves, the radii of influence and the negative effects of possibly inexact measurements in this area. They also determined the transmissivities on a monthly basis by staggering the average transmissivity over 3-months intervals in dependence on the drawdown difference Δ s.

The following possible causes for the decreasing transmissivities were investigated:

- Variations in aquifer thickness
- Changes in the formation of new ground water
- Dependence on total pump rate
- Changes in the average pump rate of the individual wells
- Lowering of water level into the pumped aquifer, i.e. transition from confined to unconfined conditions
- Influence of pumping time.

According to the investigation results obtained by IIT, some of these influences are not existing; if any were apparent, they were not able to cause a decrease in the transmissivity to such an extent. Grain size analyses which were executed prior to and after the IIT calculation did not furnish any clear indications either.

However, the results of the pump tests in which we were involved as consultants in 1977 (5) induced us to go into this problem again, paying special attention to the leakage.

3.6 Ground Water Leakage within the Mine Area

We will now deal with two superimposed aquifers which are hydraulically balanced and are separated by a layer of far lower permeability. If water is withdrawn from one aquifer, the water not only comes from this aquifer, but also from the other one. This phenomenon is known as "leakage". The flow rate q (per square unit), which is fed from one aquifer into the other, is proportional to the differential head ($\triangle p$) of the two aquifers and inversely proportional to the hydraulic resistance (c) of the separating layer (6):

$$q = \frac{\triangle p}{c}$$

were

q = flow rate per square unit of the semi-pervious layer (gallons/minute/foot^2)

$\triangle p$ = the differential head (feet)

c = the hydraulic resistance of the semi-pervious layer (minutes)

$c = M'/k'$ where M' = thickness of the semi-pervious layer (feet)

k' = permeability (hydraulic conductivity) of the semi-pervious layer (feet/minute)

The influence of the "initial gradient" is neglected (7).

Due to the low values of the k'/k ratio (about 1/10,000) - k is the permeability of the pumped aquifer - horizontal flow components within the separating layer must not be considered in this particular case (8). -

The investigation carried out prior to, after, or during the tests conducted by IIT paid little attention to the leakage factor. The most recent pump tests (1977) therefore concentrated more on the aquifer below the parting clay. They clearly demonstrated that water from the lower aquifer was seeping into the upper one (5).

The following coefficients were obtained:

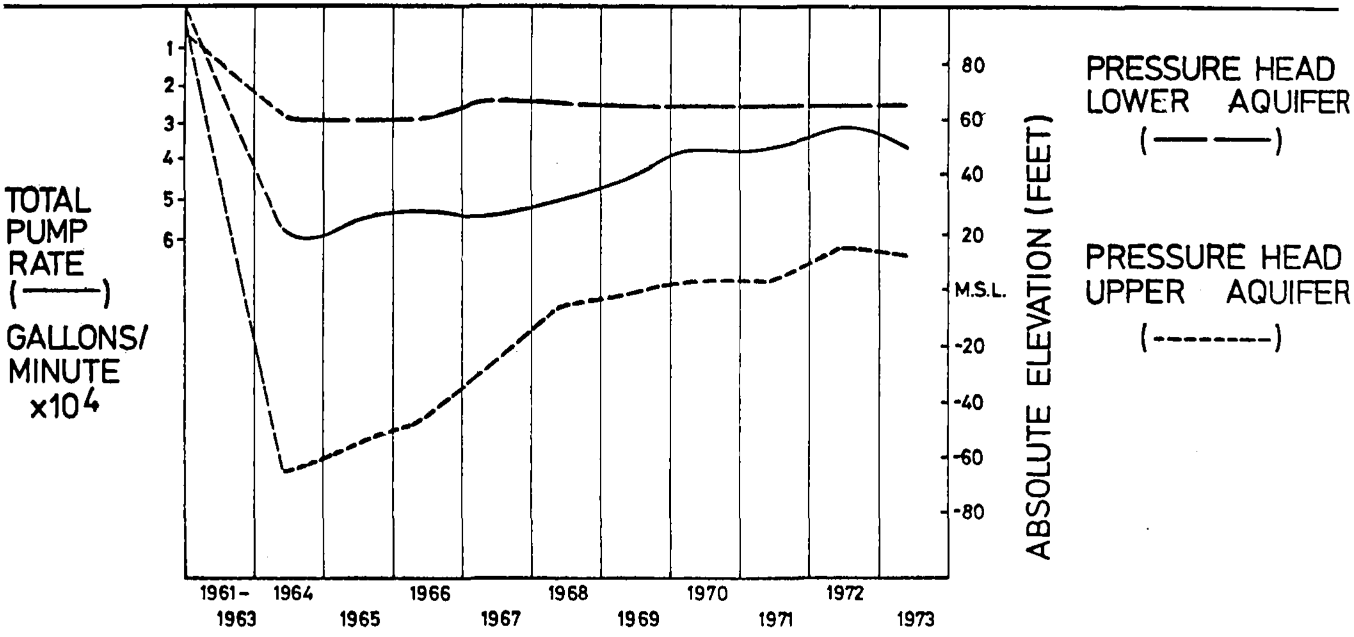

Figure 5 : VARIATION OF TOTAL PUMP RATE FROM 1964 THROUGH 1973
VARIATIONS OF PRESSURE HEAD IN UPPER AND LOWER AQUIFER
GWC OPERATIONS NEYVELI LIGNITE MINE, TAMIL NADU

	Upper Aquifer	Parting Clay
Transmissivity T (gpd/ft)	58,000	-
Storage coefficient S (-)	$1 \cdot 10^{-4}$	-
Leakage factor L (feet)	3,900	-
Hydraulic resistance c (min)	-	$3 \cdot 10^{6}$

As can be seen from the storage coefficient the upper aquifer is semi-confined or semi-unconfined, respectively. This fact in itself is not new. The precise water level measurements which NLC had been carrying out regularly since 1961 already supported this view. The hydrograph (Fig. 5) shows the variations of the hydraulic head in the two above mentioned piezometers situated near the first well row. The beginning of pumping operations did not only produce a relief in the upper aquifer (maximum 164 feet), but also in the lower one (maximum 36 feet) (also Fig. 3). This means that with sufficient lateral expansion of the parting clay, the water, in the present case, flows upwards into the pumped aquifer.

Until 1964 - when the opencast had reached its maximum extension - the total required pump rate had increased to 60,000 gallons/minute. At the same time and as can be seen, the hydraulic heads of both aquifers lowered in the well surroundings.

From 1964 onward, however, the hydrograph showed a particularity: the curbing of the total pump rate to approx. 31,200 gallons/minute - already described previously - as well as the increasing distance of the well gravity center from the piezometers caused a rise in the hydraulic head of the upper aquifer; yet, the head in the lower aquifer did not recover again after this date, it stayed at the lower level.

It is possible that due to the fact that this decrease in differential head is higher than expected, the leakage might reduce. This would be very interesting with a view towards clarifying the decrease in the apparent transmissivity which has also been observed since 1964. There is a definite connection between leakage and apparent transmissivity:

As is well known, the vertical leakage entails a flattening of the depression cone which starts near the production well; also the distance-drawdown curve gets flatter (9).

If transmissivity and leakage are calculated separately in the evaluation of the pressure head measurements as is the case, for example, with the WALTON time-drawdown method, the coefficients obtained under ideal conditions will be independent of the distance from the well (6). If, on the other hand, the leakage is not considered in the calculation, its influence is included in the coefficient which is now to be called "apparent transmissivity". The values of the apparent transmissivity are larger than the real T - as is the case when using the THIEM method. Provided all other conditions remain constant,

$$T_{app.} = f \left\{ T, \frac{1}{L} \right\}$$

where f = symbol of the function

T = transmissivity (gallons/day/foot)

L = leakage factor (feet); L is inversely proportional to the leakage-rate q!

For example, if it is assumed that an intense new formation of ground water has caused the pressure head of the lower aquifer to rise, this will result in an increase of the differential head Δp and consequently in an increase in the seeping rate through the parting clay into the upper aquifer. Although it is assumed that the production rate is kept at a constant rate, the depression cone will become even flatter there and the apparent transmissivities obtained according to THIEM will also increase.

The general rule is that if the leakage rate increases in relation to the pump rate, the apparent transmissivities will also rise when calculated with the help of piezometric measurements. Inversely, it can be said that the apparent transmissivities decrease as soon as the percentage of leakage of the pump rate goes down.

Because of this relation and the almost constant pressure head in the not directly pumped aquifer, it was decided that all the data indicating decreasing leakage in the mine since 1964 should be studied again.

3.7 Decrease in Leakage

The transmissivities and leakage factors of the opencast mine in the 60s are not available. A decision could be made if it were possible to determine the amount of leakage in its time-dependent variation based on appropriate piezometer observations and by forming the ratio between differential head and total pump rate. However, based on the assumption that the phenomenon of the pressure head remaining low was not restricted to the surroundings of the piezometers in question, it can only be supposed that as a strong lowering of the differential head Δp was registered, the leakage, being considerably influenced by Δp, decreased likewise.

This conclusion is backed by the results of the pump tests conducted in 1977 in the southeastern part of the mine area. At that time, ground water conditions were only slightly affected by ground water control: In the production well located farthest away from the mine at a distance of 1.7 miles, the pressure heads of both aquifers were almost the same before pumping with a difference of only a few inches. Hence, as far as this well is concerned, it can be assumed that the calculated mean leakage coefficient, L = 3900 feet, is not influenced by too strong a ground water flow, but is more or less undisturbed.

For testing the effective leakage properties within the mine proper with regard to the year 1977, the drawdowns in numerous wells and testpoints during the aquifer drainage were controlled mathematically, applying the value L = 3900 feet. A short explanation of the calculations is given below.

We used the DE GLEE formula ((6), also JACOB (8)):

$$s_m = \frac{Q}{2\,\pi\,T} \cdot K_o\left(\frac{r}{L}\right)$$

were s_m = steady-state drawdown in a piezometer or in a well (feet)

Q = discharge rate of the pumped well (gallons/day)

T = transmissivity (gallons/day/foot)

L = leakage factor (feet)

r = distance from the pumped well (feet)

$K_o\left(\frac{r}{L}\right)$ = modified BESSEL function of the second kind and of zero order (=HANKEL function)

Since it is the steady-state flow which is described by the series, the storage coefficient and the pumping time are not considered as they are important only during the non-steady-state flow.

Since the partial differential equation governing the DE GLEE formula is linear (8), this formula and the principle of superposition can be used to obtain solutions for any number of pumping wells (10).

In the computation, the HANKEL function was replaced by a convergent series (11). If both partial series are only used up to the 10th power, the DE GLEE formula being prepared for superposition is as follows:

$$
\begin{aligned}
s^*_{mn} = \frac{Q_n}{2\,\pi\,T} \cdot \Bigg\{ & -(0.5772 + \ln\frac{r_n}{2L}) \cdot \Big[1 + (\frac{r_n}{2L})^2 + \\
& + 0.25(\frac{r_n}{2L})^4 + 0.0278(\frac{r_n}{2L})^6 + 0.00174(\frac{r_n}{2L})^8 + \\
& + 0.000764(\frac{r_n}{2L})^{10}\Big] + (\frac{r_n}{2L})^2 + 0.375(\frac{r_n}{L2})^4 + \\
& + 0.0509(\frac{r_n}{2L})^6 + 0.00362(\frac{r_n}{2L})^8 + \\
& + 0.000159(\frac{r_n}{2L})^{10}\Bigg\}
\end{aligned}
$$

s^*_{mn} = steady-state drawdown at the testpoint, caused by pump well N° n (feet)

Q_n = pump rate of well N° n (gallons/day)

T = transmissivity of the pumped aquifer (gallons/day/foot)

r_n = distance from the pump well N° n (feet)

L = leakage factor (feet)

The total drawdown, s^*_m, at the testpoint results from the following superposition:

$$s^*_m = \sum_{n=1}^{n=z} s^*_{mn}$$

(z = number of wells)

Coordinates are used in the calculation program so that the drawdown of the pressure head produced by the well field can be calculated for any point desired.

The testing of the effective leakage properties as they appeared in the mine area in 1977 used the 1977 pump rate, Q, and the 1977 r values. The transmissivity, T, and the leakage factor, L, were taken from the pumping tests carried out that same year.

A comparison of the calculated water levels of the upper aquifer with those measured in the mine area showed that there was no conformity at all. The calculated drawdown values proved to be much too low.

The conformity can only be achieved if - with T being constant - the leakage factor is not entered with L = 3,900 feet but with L = 8,000 feet. This reflects a lower leakage (The leakage factor is inversely proportional to the seeping leakage rate).

The consideration of the fluctuations of T obtained from the pump test evaluation (maximum ± 20 %) and the use of the relation

$$L^2 = T \cdot c$$

(c being the hydraulic resistance of the parting clay) leads to the conclusion that the leakage in the mining area must be lower than the pump tests have shown.

Besides the hydrograph, these calculations provided an additional indication pointing out that the observed decrease in the apparent transmissivity might, at least in part, be a result of the declining leakage.

3.8 Hydrological Model of the Leakage in the Area of the Lignite Deposit - Conclusions

Both WALTON (6) and BOULTON (6) described the pressure

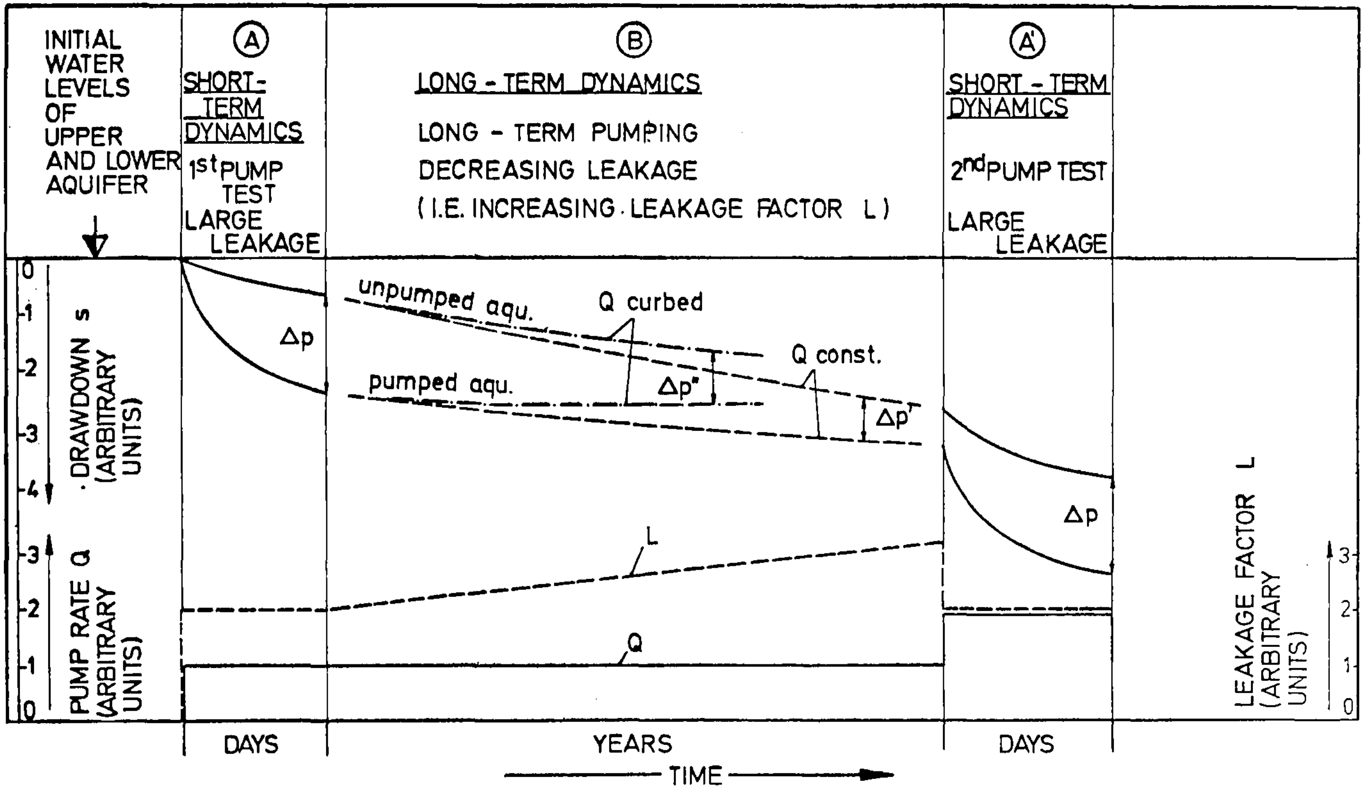

Figure 6 : GROUNDWATER LEAKAGE ACCORDING TO SHORT - TERM AND LONG - TERM DYNAMICS

conditions in a pumped confined aquifer under the influence of leakage. WALTON takes the pressure in the unpumped aquifer as being constant; BOULTON, on the other hand, permits lowering of the water level (secondary cone). This results in a very important difference: in the first case, the water level in the pumped aquifer (primary cone) reaches the steady state after a certain period of time; in the BOULTON model, however, it reaches a temporary stability and then sinks continuously until at least one of the cones reaches a recharging area with sufficiently abundant water.

The reason for the continuous lowering of the water level is that the secondary cone also spreads out. The same thing happens with the isolines of differential head and the isolines of horizontal flow volume within the pumped aquifer. Because of increasing friction losses in the aquifer, the pressure head in the pump well continues to sink (12).

At a successive decreased discharge, too, the secondary cone can change to such an extent that the differential head sinks lower than would be necessary to keep the leakage factor constant. As a result of this, the leakage decreases.

Based on this concept according to BOULTON, the decrease in leakage in the openpit mine might be explained by the pumping at a high pump rate which occurred over a period of years.

The results of the pumping tests should now be considered again.While the effective leakage in an openpit mine may have decreased down to a small amount due to a strongly decreasing differential head, non-steady pumping tests carried out directly within the influential reach of the aquifer drainage may indicate a leakage several times higher. The following reasoning provides an explanation.

When comparing leakage values calculated from observed drawdown data, whether obtained through pump tests or from the aquifer drainage data, the duration of the decrease must be particularly considered. In general, a difference must be made between short-term and long-term dynamics. In comparison to the case described above of long-term drawdown of the water level in the mine area (Fig. 6, Section B, differential head $\Delta p'$ or $\Delta p''$), a pump test will show (both in the pumped and in the unpumped aquifer) drawdowns of completely different dimensions. For these dimensions, it is almost negligible whether the pump test started out from the initial water level (Section A), or whether it increased already existing drawdowns (Section A'; please note the different time units). In both cases, the leakage resulting from Δp will be considerably greater than the leakage resulting from long-term dynamics at a smaller $\Delta p'$ value. The same applies to the $\Delta p''$ value which results when the pump rate is curbed (Section B).

This explains the difference between the leakage value obtained through pumping tests and the actual leakage existing in the mine itself. It also explains why the pumping tests did not also indicate the phenomenon of decreasing leakage.

The formation of the secondary cone could be abandoned altogether when making the evaluation according to WALTON, since the decrease was less than 5% of the entire thickness of the lower aquifer. The equilibrium observed during the pumping tests was possibly the same equilibrium which appeared at times in the evaluation according to BOULTON. Under the conditions prevalent in 1977, it was neither necessary nor possible to continue pumping.

Between 1961 and 1964, when more or less constant "apparent transmissivities" were calculated, the decrease - if any - in leakage may have remained undiscovered due to the continuous increase in the total pump rate.

The above results lead to the following considerations:

- When comparing leakage values, the corresponding pumping time on which the figures are based must be considered.
- With pumping tests within the mine area, it is possible that a higher leakage rate will be calculated although the effective leakage is considerably lower.
- Pumping tests where an equilibrium appears can be evaluated according to either WALTON or BOULTON, but a long-term prognosis can only be made after pump tests which clearly show without a doubt whether in the long run the leakage will decrease or not.

For the time being, the planning of the future ground water control makes allowance for the effect described above by extrapolating the falling apparent transmissivity into the future. -

It is not the aim of this paper to establish a quantitative connection between the course of the pressure head (Fig. 5) and the difference in the calculated numbers of L. This can only be possible when further pump tests can be executed. It was only our intention to point out an interesting aspect of mine drainage.

This aspect is all the more important as the experience gained by clarifying the hydrological and hydrogeological causes of leakage decreases might be transferred to other opencast mines. Thus it might be possible in the future to avoid overdimensioning of drainage installations.

4. RESUMÉ

An overall view is first given of what experience has shown to be the most important operations in the planning of an openpit drainage. Here we find three main divisions: protection against ground water; protection against water at the ground surface; and protection against water within the openpit. The main objectives to be reached are mentioned as well as the necessary operations and intermediate results.

Not only must the mine be protected from disrupted natural conditions. The environment too must be protected from the openpit mine. For this reason, the subjects of environmental protection, protection of human water needs and claims are briefly mentioned.

As an example of one of the numerous problems which arise, and using for this example the lignite openpit mine in the Cuddalore Basin in India, the possible changes in leakage with time are discussed. It has been proved that leakage appears during the pressure relief of the upper of two aquifers under the lignite layer, separated from each other by a semi-permeable clay layer. Prior to pumping, both hydraulic pressure heads were approx. 110 feet above the lignite. Ground water control operations were started in 1961. Only the upper aquifer was pumped; the pressure head was sunk down to below the lignite. By 1964, when the mine reached its greatest expanse, the total required pump rate rose to 60,000 gallons/minute, but decreased to 31,200 gallons/minute by 1976 (US gallons).

At the same time, the apparent transmissivity of the upper aquifer, calculated according to the equilibrium THIEM method, sank from 135,000 to 77,000 gallons/day/foot.

At a constant transmissivity, two things indicated that a decreasing leakage might be present: The lowering of the pressure in the unpumped aquifer remained in its lowered state even after decreasing the total pump rate and in spite of a rise in pressure in the pumped aquifer. Moreover, in the most recent pump tests carried out in 1977 at a distance of 1 to 2 miles beyond the openpit itself, a leakage factor of L = 3,900 feet was calculated (according to WALTON), while at the same time the figure of the mine area was L = 8,000 feet (JACOB/DE GLEE). (Leakage is converse to the leakage factor).

A hydrological model of the lignite deposit area in the Cuddalore Basin based on BOULTON's concepts of the semi-confined aquifer may possibly explain the questions and contradictions through decreasing leakage. In the empirical evaluation of leakage values, a distinction must be made between short-term and long-term dynamics. Pump tests may provide considerably high leakage though real leakage in the mine area will be very low. This leads to the conclusion that caution should prevail when making prognoses based on leakage values obtained through pumping tests.

Conclusive statements and quantitative data can only be made after further pumping tests. Since decreasing leakage would permit a reduction in the required pump rate, cost savings would be possible and could possibly be planned. Similar effects can also be expected during the operation of other openpit mines.

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