Pore Pressure

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Received: September 23, 2004 **Accepted:** December 10, 2004

Abstract: To define pore pressure properly, the geological situation of a given coal mine should be known. Layer pressures of rock and aquifers of the Slovenian coal mines are well known generally. To choose an excavation method and assure safe working conditions, however, the knowledge of layer pressures both above and beneath coal is essential. In spite of the fact that layer pressures and indirectly also pore pressures of rock and aquifers of the Slovene coal mines are well known, overpressures can be defined quite precisely by using a model which is applied to the execution of deep boreholes. Under the assumption that the construction of a borehole is an intervention into a space of ''infinite'' dimension in comparison with the diameter of the borehole, a one-dimension model can be applied.

Keywords: pore pressure, borehole, layer pressure, overpressure, one-dimensional model.

Introduction

The extraction of coal is associated with problems of safe and economical mining under aquiferous rock. Convenient technological solutions of dewatering from the surface or from the pit can contribute decisively to an adequate fulfillment of both safety and economy requirements. Problems of safe excavation of coal under aquiferous rock have been already successfully overcome all over the world by means of surface dewatering facilities - wells. The construction of surface wells is relatively simple and does not require any special technological interventions.

To dewater aquiferous rock above coal from the pit, however, the technology of construction of vertical and inclined drive-in filters has been accepted recently. The drive-in filters are drilled into a roof or a bottom of a mining cavity. They are classified as main and secondary dewatering structures - in the latter case they are dewatering certain segments of aquiferous rock - or as monitoring drill holes - piezometers. The implementation of drive-in filters from the pit is much cheaper than the one from surface wells, because drive-in filters are comparatively shorter. The construction of drive-in filters requires special technological measures in all cases of drilling through rock with high pore pressures (above 20 bar).

After analysing the requirements for drive-in filters, the use of the equipment conform-

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ing to the valid respective standards has been foreseen. The drive-in filter equipment has been dimensioned to sustain all mechanical loads as well as layer and pore pressures. The following advantages were gained by its choice:

- drilling by using drive-in filter pipes;
- installation of a drive-in filter by means of hydraulic pressure which is -considering conditions - correspondingly greater than pore pressure;
- effective activation of a drive-in filter;
- effective dewatering through a drive-in filter.

To define pore pressure properly, geological situation of a given coal mine should be known. Layer pressures of rock and aquifers of the Slovene coal mines are well known generally. To choose an excavation method and assure safe working conditions, however, the knowledge of layer pressures both above and beneath coal is essential. In spite of the fact that layer pressures and indirectly also pore pressures of rock and aquifers of the Slovene coal mines are well known, overpressures can be defined quite precisely by using a model which is applied to the execution of deep boreholes. Under the assumption that the construction of a borehole is an intervention into a space of ''infinite'' dimension in comparison with the diameter of the borehole, a one-dimension model can be applied.

PHYSICO-MECHANICAL PROPERTIES OF ROCK

To determine pore pressures governing within aquiferous layers of rock precisely enough, the following properties of rock must be known:

- compressive strength
- hardness and abrasiveness
- rock pressures
- elasticity
- adhesion
- permeability
- layer fluids and pore pressure
- porosity
- temperature

Based on a good knowledge of physico-mechanical properties of rock in the Slovenian coal mines, the most often encountered problems associated with the construction of drive-in filters are as follows:

- unconsolidated sand layers
- dispersive layers
- plastic and liquid layers
- swelling layers
- low-pressure zones
- high-pressure zones

Unconsolidated sand layers

Unconsolidated sand layers exert exclusively a physical effect on a drilling fluid. The drilling fluid becomes saturated with sand and can hardly be maintained at the drilling conditions in a mine. The problem of stability of the borehole wall arises, bringing about a high increase in the borehole diameter in comparison to the diameter of a drilling crown. In such cases, drilling fluid with high rheological and thixotropic properties is recommended. The gelled drilling fluid is retained within the zones of increased diameter preserving the borehole stability. Because these layers are sensitive to variations of hydrostatic pressure, fast backreaming of drilling tools from the borehole should be avoided.

Dispersive layers

Dispersive layers are usually poorly consolidated marly clays and marls of foliated structure. Clays with a low content of montmorillonite are subjected to dispersion too. These layers are crumbling during the drilling process and widening of the borehole result. The phenomena occur in cases of steeply sloped as well as tectonically crushed layers. When drilling through the layers mentioned, the flow of drilling fluid should be maintained within the laminar domain. Low velocity of drilling fluid through the interspace between the drilling tool and the borehole wall does not allow a good cleaning of the borehole. In such cases, "n" values, rheological properties, and kinds of drilling fluid should be adjusted to layers being drilled through.

A good cleaning of the borehole and minimum erosion of its wall is achieved at "n"-values between 0.5 and 0.7. In the case of thus adjusted drilling fluid, any underpressure or overpressure created during dropping or rising of drilling tools in the borehole should be avoided.

Plastic and liquid layers

These layers of clay usually consist of irregularly sedimented minerals illite and kaolinite. Clays can bind large quantities of water during sedimentation. They can start flowing into the borehole as soon as the hydrostatic pressure in the borehole drops below the layer pressure or due to additional hydration caused by a drilling fluid respectively.

If the density of a drilling fluid is too low these clays may cause drilling tools to become stuck and in extreme cases penetrate into higher layers in the borehole. The said consequences can be avoided by using a drilling fluid with a suitable overpressure with regard to the layer pressure expected in the borehole.

Swelling layers

Contrary to liquid clays, the swelling ones are not hydrated but only absorb water in great quantities. They exert a high cation exchange capacity and are sensitive to the penetration of filtrate as well as type and concentration of electrolyte contained in the filtrate. The sensitivity of clays to the drilling fluid density is of a secondary importance. Properly prepared polymeric drilling fluids are the most suitable for drilling through layers of swelling clays.

Low-pressure zones

When drilling through low-pressure zones, a danger of loss of drilling fluid or respective loss of its circulation flow exists. The loss of drilling fluid occurs most often at the bottom of the borehole under the drilling crown but this is not a common rule. It may appear anywhere along the borehole as a result of physical properties of a drilling fluid or occasional release of underpressure in the borehole. It is important therefore to know the type of layer where the loss of drilling fluid might occur.

A partial loss of drilling fluid is a phenomenon where the volume of the return drilling fluid is smaller than the volume of the drilling fluid being pressed into the borehole. A complete loss of drilling fluid means that there is no return flow of the drilling fluid from the borehole.

Unconsolidated layers

These are layers of sand and clayey slate. Partial losses of drilling fluid usually occur in sands with average permeability coefficients around 3-4 x 10^{-4} m/s. The complete loss of drilling fluid appears at the permeability coefficient of 10^{-2} m/s.

Permeable layers

There exist well-consolidated layers in nature where partial losses of drilling fluid still may occur. A typical example of such a layer is dolomite.

Naturally fissured layers

Fissures can be created within a layer by a natural process and can exist in all layers.

Occasionally fissured layers

Such a type of fissures can occur in rock containing zones of lower strength. Fissures can result from elevated density of drilling fluid, from positive pressure impulses in cases of dropping drilling rods or protection pipes in the borehole and from fast pumping of drilling fluid into the borehole.

Cavernous layers

These layers usually occur in limestone. A typical property of such layers is that after penetration of the drilling crown for some centimetres or metres into rock, a quick and complete loss of drilling fluid occurs.

High-pressure zones

If the hydrostatic pressure of the column of a drilling fluid is lower than the layer pressure in the borehole, the inflow of a layer fluid into the borehole will take place. Such inflows cause a displacement of the drilling fluid from the borehole. The borehole should be closed as soon as the inflow of the layer fluid is observed. After the closure, the layer fluid should be cleaned from the borehole. The above process is called the controlled eruption of fluid from the borehole.

In case the borehole mouth cannot be closed in time, the phenomenon of uncontrolled eruption takes place.

The optimum drilling of drive-in filters should assure the following:

- right prediction of high-pressure zones
- adjustment of density of drilling fluid
- monitoring of all phenomena in the borehole during the drilling process.

The best effects are obtained by using a drilling fluid, which is creating a hydrostatic pressure slightly higher than the layer pressure. The following *Table I* is showing the effect of gas presence in the drilling fluid on the reduction of its density and, consequently, on the reduction of its hydrostatic pressure.

Table 1. Reduction of the hydrostatic pressure.

REDUCTION OF HYDROSTATIC PRESSURE DUE TO THE PRESENCE OF GAS IN DRILLING FLUID AT THE DEPTH OF 500 m					
Density of outflowing drilling fluid (kg/m^3) and the level of reduced pressure Δp (bar)					
ρ_i=1200 p_{ht}=58.86	1000	0.814	ρ_I=1600 p_{ht}=78.48	1400	0,6226
	800	2.035		1200	1.4526
	600	4.070		1000	2.5958

$$\Delta p = 2.3 \cdot \frac{\rho_1 - \rho_2}{\rho_2} \cdot \log p_{ht} \quad (1)$$

It should be noted that the calculation is valid for a 500 m deep borehole. As drive-in filters are drilled from mine haulageways and the hydrostatic pressure of a drilling fluid with the density of 1200 kg/m^3 in a 100 m deep mine borehole amounts to about 12 bar, a gas eruption from the borehole might occur in a short time.

To define pore pressure properly, geological situation of a given coal mine should be known. Layer pressures of rock and aquifers of the Slovenian coal mines are well known generally. To choose an excavation method and assure safe working conditions, however, the knowledge of layer pressures both above and beneath coal is essential. The creation of a normal layer pressure is shown on a simplified model on the Figure 1a. Normal sedimentation or respective deposition of layers has been taking place through geological eons. Water was captured between sediments in this process under the pressure equal to:

$$p_w = \rho_w \cdot g \cdot H + p_0 \quad (2)$$

When the pore pressure equals the theoretical hydrostatic pressure, it is called the normal pore pressure.

Aquiferous layers in which elevated pressures are governing or overpressure has been created are often encountered during drilling. The creation of overpressure is shown on a simplified scheme on the Figure 1b. Overpressure can also result from chemical processes through geological eons or from tectonic rupture.

In spite of the fact that layer pressures and indirectly also pore pressures of rock and aquifers of the Slovene coal mines are well known, overpressures can be defined quite precisely by using a model which is applied to the execution of deep boreholes. Under the assumption that the construction of a borehole is an intervention into a space of ''infinite'' dimension in comparison with the diameter of the borehole, a one-dimension model can be applied. Let us suppose that at a certain depth of our model, pressure is acting in the cylinder, causing also a direct increase of pore pressure of captured water in this manner (Figure 2).

Thus, overpressure is defined according to the following equation:

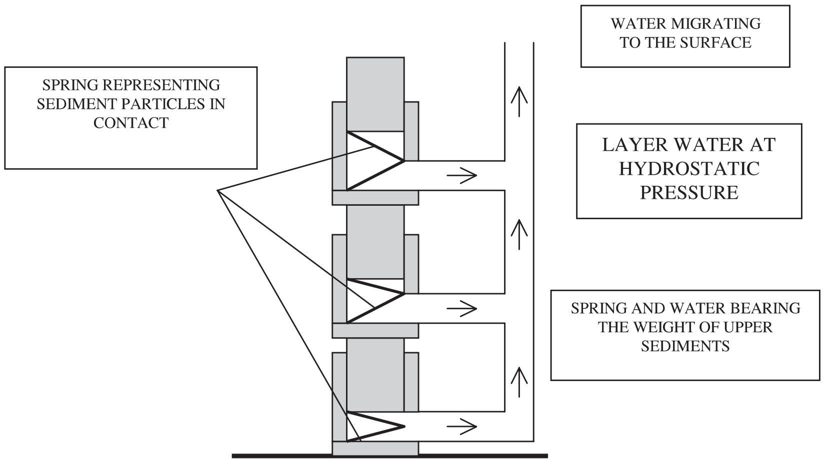
$$\sigma_{ob} = \sigma_z + p_p \quad (3)$$

Where

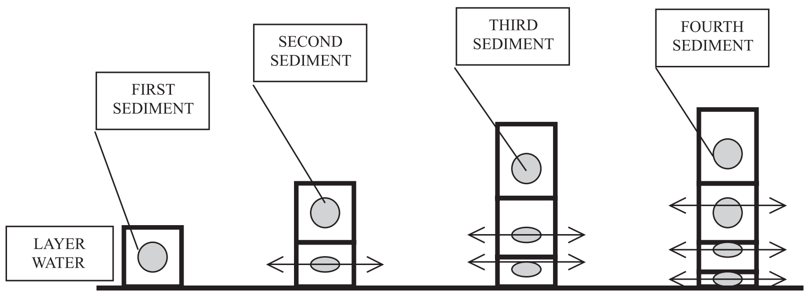
σ_{ob} overpressure or geostatic loading of rock

σ_z loading between two sediments

p_p pore pressure.



a) Mechanical representation



b) Schematic representation

Figure 1a. Creation of normal layer pressure.

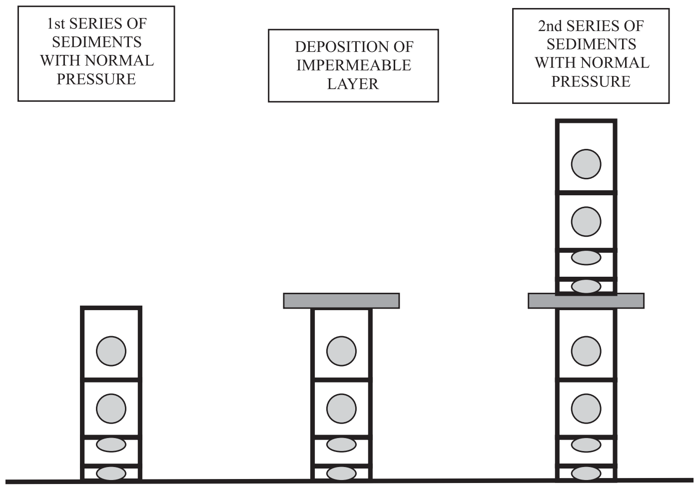


Figure 1 b. Creation of overpressure within a layer

A high pore pressure develops, when vertical geostatic loading increases and water remains captured between sediments. Vertical overpressure depends on rock pressure at the depth H_m of a sediment with a given density ρ_m.

$$\sigma_{ob} = \int_0^{H_m} \rho_m \cdot g \cdot dH \qquad (4)$$

Density of sediment depends on rock density ρ_s, pore density of fluid ρ_{fl}, and porosity ϕ, according to the following equation:

$$\rho_m = \rho_s(1-\phi) + \rho_{fl}\phi$$
$$\phi = \frac{\rho_s - \rho_m}{\rho_s - \rho_{fl}} \qquad (5)$$

Density of sediment on a given region where exploitation and test drilling is often performed is determined by means of conventional borehole logging. The variation of sediment density with depth affects the porosity of rock. Borehole logs in homogeneous rock have shown that average porosity decreases with depth while densities of pore fluid and sediment, on contrary, increase.

The usual method for determination of the average porosity,f, from the geophysical measurements taken in the borehole is based upon the exponential equation. Average density of sediment ρ_m is determined from the borehole log and average porosity is expressed in the same manner (Figure 3).

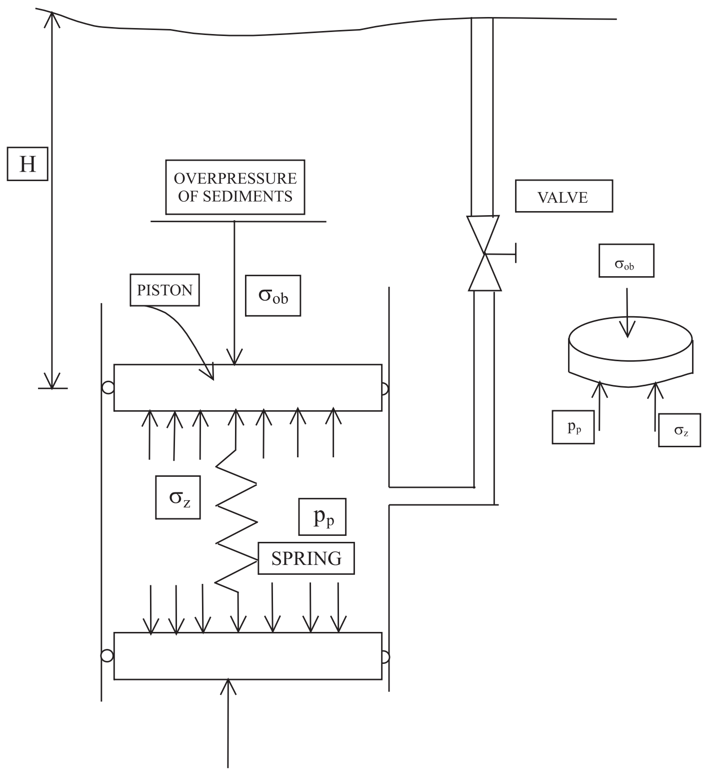


Figure 2. One-dimensional model of pore pressure definition.

The equation of the straight line for average porosity is:

$$\phi = \phi_0 \cdot e^{-\kappa H_\infty} \qquad (6)$$

Where:

ϕ_0 surface porosity
κ porosity reduction constant
H_m sediment depth

$$\kappa = \frac{\ln \phi_0 / \phi}{H_m} \qquad (7)$$

Geostatic pressure acting on the sediment is expressed by the equation:

$$\sigma_{ob} = g \int_0^{H_\infty} \left[\rho_s (1-\phi) + \rho_{fl}\phi \right] dH \qquad (8)$$

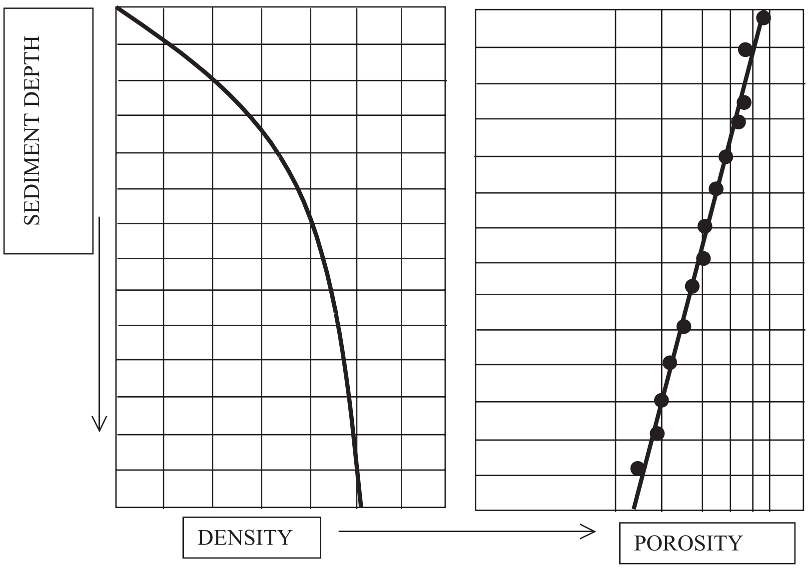


Figure 3. Determination of density and porosity as a function of sediment depth.

After replacing porosity, ϕ, with surface porosity, ϕ_o, it follows:

$$\sigma_{ob} = g \int_0^{H_m} \left[\rho_s \left(1-\phi_0 \cdot e^{-\kappa H_m}\right) + \rho_{fl} \cdot \phi_0 \cdot e^{-\kappa H_m} \right] \cdot dH \qquad (9)$$

$\Rightarrow$

$$\sigma_{ob} = \rho_{s\cdot} \cdot g \cdot H_m - \frac{(\rho_s - \rho_{fl}) \cdot g \cdot \phi_0}{\kappa} \cdot \left(1 - e^{\kappa H_m}\right)$$

With the determination of vertical geostatic pressure the information precise enough is obtained to assess conditions, which may be expected for the construction of a drive-in filter.

Conclusion

One must be aware of being exposed to rock, hydrostatic, and pore pressures under the surface of earth. All these pressures should be under control during the intervention in rock, foreseen for the execution of a borehole, which will act as a dewatering facility or a piezometer. By the determination of expected pore pressures governing within an aquifer and by optimization of hydraulic and rheological parameters of a drilling fluid, boreholes can be carried out successfully from mine haulageways nowadays.

To determine the pore pressure of an aquiferous layer, the one-dimensional model represented in the paper is sufficient. In the case of drilling on well-investigated regions, the calculation of pore pressure according to the model and the interpretation of borehole logs will be indicators sufficient enough for the prediction of conditions governing within aquifers having high pore pressures.

Symbols and units

SYMBOL	*MEANING*	*DIMENSION*	*SI UNIT*
g	Gravitational acceleration	LT^{-2}	m/s^2
H	Borehole depth	L	m
H_m	Sediment depth	L	m
p_p	Pore pressure	$ML^{-1}T^{-2}$	Pa
p_w	Hydrostatic pressure of water	$ML^{-1}T^{-2}$	Pa
p_{ht}	Hydrostatic pressure	$ML^{-1}T^{-2}$	Pa
p_0	Atmospheric pressure	$ML^{-1}T^{-2}$	Pa
ϕ	Porosity	-	-
κ	Porosity reduction constant	L^{-1}	1/m
ρ_i	Density of drilling fluid	ML^{-3}	kg/m^3
ρ_m	Rock (sediment) density in water	ML^{-3}	kg/m^3
ρ_s	Rock density	ML^{-3}	kg/m^3
ρ_w	Water density	ML^{-3}	kg/m^3
ρ_{fl}	Density of pore fluid	ML^{-3}	kg/m^3
σ_z	Loading between sediments	$ML^{-1}T^{-2}$	Pa
σ_{ob}	Overpressure, geostatic loading of rock	$ML^{-1}T^{-2}$	Pa

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