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Calculations regarding the application of isolating and retaining seals with culverts

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Abstract. The paper presents the calculations pertaining to the application of isolating and retaining seals with culverts, allowing to control the flow of water, protecting the water drainage dip heading against uncontrolled ingress of water accumulated in the neighbouring post-exploitation workings. The binding material used in the construction of the isolating and retaining seal with a culvert is a Bingham plastic which exerts hydrostatic pressure on the wall of the steel culvert during binding. During that time, the culvert constitutes an internal formwork. Due to the above, the calculations regarding the isolating and retaining seal were divided into two stages. In the first stage, the required length and strength of the seal were determined based on analytical and numerical calculations, depending on the expected maximal water pressure. In the second stage of calculations, the necessity to apply the binding material onto the seal in stages was exhibited, due to hydrostatic pressure exerted on the culvert pipe by the Bingham plastic. The thickness of each of the layers of the binding material has been specified based on static analyses of the culvert pipe, considering the binding time of the applied material.

1. Introduction

In case of coal mine liquidations, it is often assumed that the natural inflow of water to its area should be redirected to the main drainage system of a neighbouring active mine.

Mines “X” and “Y” were operating as separate plants until February 29th 2004 and were subsequently merged into a “X-Y” two-division coal mine. In May of 2006, the liquidation of the “Y” division was commenced. The natural inflow of water to that division was approx. 1.3 m³/min. To prevent the water hazard posed by the liquidated “Y” division to the neighbouring active mines, it was necessary to drain the workings by directing the water through the R drainage dip-heading (figure 1). The R drainage dip-heading allows for controlled redirecting of water flowing into the workings of the “Y” division to the main drainage system of the “X” division [1].



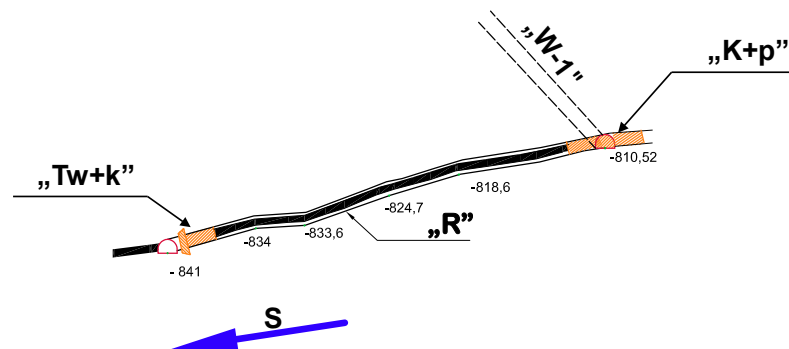


Figure 1. Locations of the water stopping and retaining and isolating seals: (R) – drainage dip-heading, (W-1) – technological cross-cut, (S) – water flow direction, (Tw+k) – water stopping and retaining and isolating seal, (K+p) – retaining and isolating seal with a culvert.

To isolate the workings of the liquidated “Y” division, two protections were designed, namely the (K+p) isolating and retaining seal with a steel pipe culvert with a diameter of 2.0 m located in the area of the intersection of the drainage dip-heading and the entry to the W-1 cross-cut as well as the water stopping combined with a full isolating and retaining seal located approx. 20 m before the water off-take location (figure 1). The flow of water will be controlled mostly at the stopping combined with the isolating and retaining seal (Tw+k).

The paper presents the method of calculations pertaining to the application of the isolating and retaining seal with a steel culvert, allowing to control the flow of water, protecting the water drainage dip heading against uncontrolled ingress of water accumulated in the neighbouring workings.

2. The method to determine the required length and strength of isolating and retaining seals

The determination of geometrical and strength parameters of isolating and retaining seals is performed based on methods required by standards and on analytical and numerical calculations [1, 2].

Depending on the applied materials, the following types may be distinguished [3]:

- isolating and retaining seals made of mixtures of power-plant ash and water; power-plant ash; water and cement and other approved materials;
- isolating and retaining seals made of special and quick-setting mixtures;
- concrete isolating and retaining seals.

To verify the stability and watertight properties of the isolating and retaining seal, solutions applied in hydromechanics of hydraulic structures may be used, where the liquid pressure is one of the types of loads exerted on hydraulic structures, decisive for their stability. A hydraulic structure may lose its stability due to tipping or sliding on the substrate. The loads exerted on the structures may generally be divided into loads disturbing and supporting their balance. The basic loads disturbing the balance include hydrostatic water pressure, while the weight of the building is the basic force supporting the balance. The stability due to the slip results from the forces causing the displacement of the structure on the substrate, where the allowable shearing stress shall be exceeded. The slip of the structure is prevented by friction forces caused by the substrate. These forces have to balance the horizontal forces (liquid pressure in that case).

The stability condition of an isolating and retaining seal in view of ensuring its retaining function may be presented as a dependence [3]:

$$\begin{aligned} R &\leq P_k \\ P_k &> R_t \end{aligned} \quad (1)$$

where:

R – pressure exerted on the seal, MN/m²,

P_k – load bearing capacity of the isolating and retaining seal, MN/m²,

R_t – the shear strength of the isolating and retaining seal material, MN/m².

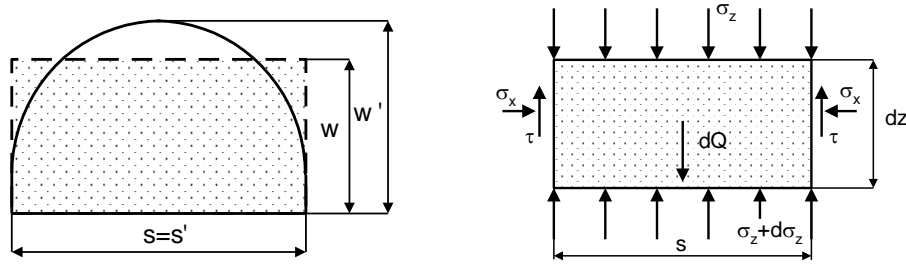


Figure 2. Calculation diagram of technical parameters for retaining seal [4].

The load bearing capacity of the seal for the load model as presented in figure 2 may be calculated using the formula [4]:

$$\begin{aligned} P_k &= \left(\frac{\gamma - B}{A} \right) \cdot [1 - \exp(-A \cdot w)] \cdot s \cdot d \cdot \mu_0 + \\ &+ \left\{ \left(\lambda \cdot \frac{\gamma - B}{A} \right) \cdot [1 - \exp(-A \cdot w)] - (1 - \lambda) \cdot \frac{B}{A} \right\} \cdot w \cdot d \cdot \mu_0 \end{aligned} \quad (2)$$

where:

$$\lambda = \frac{1 - \sin \varphi}{1 + \sin \varphi}$$

$$A = 2\mu_0 \lambda \frac{s + d}{s \cdot d}$$

$$B = 2\lambda c \frac{s + d}{s \cdot d} \frac{\mu_0}{\mu}$$

μ – internal friction coefficient of the seal material,

γ – volumetric weight of the seal material, MN/m³,

μ – internal friction angle of the seal material,

d – length of the isolating and retaining seal, m,

μ_0 – coefficient of friction of the seal material caused by the sidewalls and floor of the working,

$\mu_0 = \tan \phi_0$,

ϕ_0 – friction angle of the seal material in relation to sidewalls and floor of the working, degree,

λ – lateral expansion coefficient,

$$\lambda = \frac{1 - \sin \varphi}{1 + \sin \varphi},$$

c – cohesion of the isolating and retaining seal's material, kN/m².

3. Strength of the isolating and retaining seal with a steel culvert

The determination of the required strength parameters of the isolating and retaining seal located in the R drainage dip-road at the intersection with the W-1 technological cross-cut may be conducted based on the results of the verifying numerical calculations. Based on the analysis of water flow in the liquidated “Y” division, it should be assumed that the load bearing capacity of the seal should allow for the transmission of the maximal water pressure of 3.2 MN/m^2 [1].

The numerical calculations for the designed isolating and retaining seal were performed for a numerical model representing the geometry in vertical section through the central part of the seal located in the R drainage dip-heading at the intersection with the W-1 technological cross-cut, that is, the location that is least favourable in terms of strength (figure 3).

The calculations were conducted using the finite elements method for a flat numerical model constructed of 12522 elements connected to 6440 nodes, for flat strain conditions.

The model represents a flat section through the isolating and retaining seal placed at the intersection of the the W-1 technological cross-cut and the R drainage dip-heading, including a pipe culvert with a diameter of 2,0 m and wall thickness of 0,005 m (figure 4).

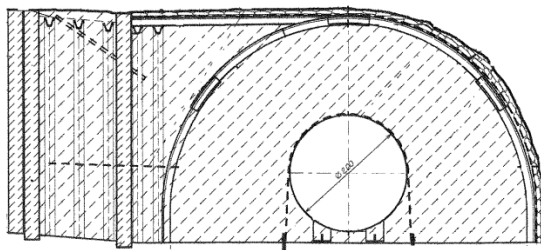


Figure 3. Cross-section of the isolating and retaining seal with a culvert.

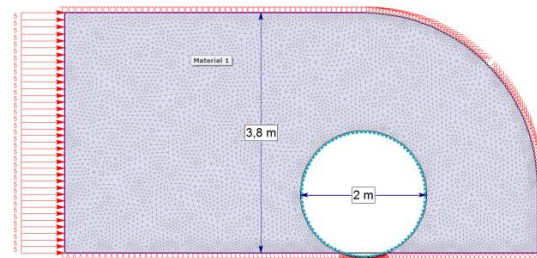


Figure 4. Numerical model of the isolating and retaining seal with a culvert assumed for the calculations.

For the model, a plastic-elastic constitutive model was assumed with the Coloumb-Mohr strength criterion and the properties assumed for the model corresponded to the calculated parameters of the binding material with a compressive strength of 15 MN/m^2 .

To represent the water pressure exerted on the designed isolating and retaining seal, a pressure increasing in subsequent simulation stages from 0.5 to 3.2 MN/m^2 was exerted on the left edge of the model (figure 4). The most important criterion adopted in the assessment of the correctness of the designed solution is the transmission of the pressure of the water accumulating in the post-exploitation workings at the side of the W-1 cross-cut by the isolating and retaining seal as well as the tightness of the seal. The fulfilment of the assumed requirements is largely dependent on the effort condition determining the formation of plastification zones (damages) in the binding material of the isolating and retaining seal.

The calculation results of the damage zones in the isolation and retaining seal have been presented in figures 5-8. The damages of the binding material have been marked in red.

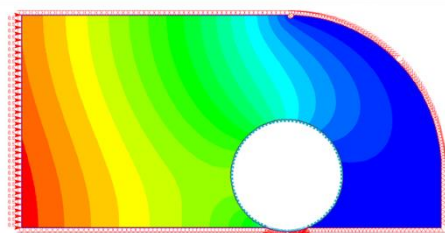
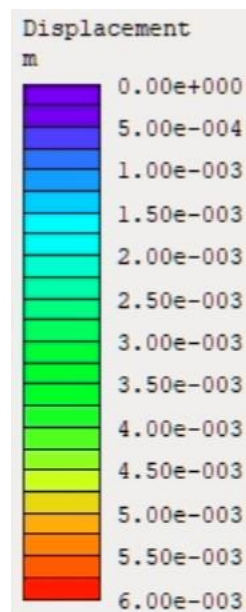


Figure 5. The calculated plasticisation zones and displacement for the model loaded with a pressure of 0.5 MN/m².

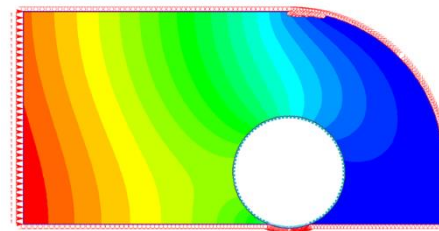


Figure 6. The calculated plasticisation zones and displacement for the model loaded with a pressure of 1,0 MN/m².

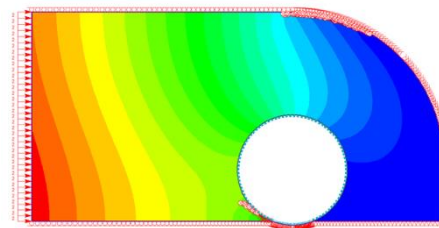


Figure 7. The calculated plasticisation zones and displacement for the model loaded with a pressure of 2,0 MN/m².

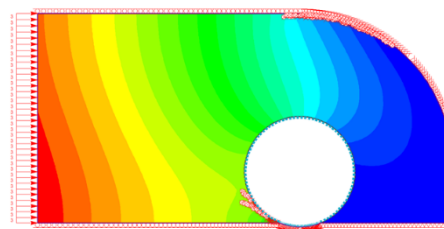


Figure 8. The calculated plasticisation zones and displacement for the model loaded with a pressure of 3.2 MN/m² of.

The obtained results indicate that in case of the first two variants of loads exerted on the isolating and retaining seal (loads from 0.5 to 1.0 MN/m²), the plasticisation has only occurred in the top part of the model, at the contact point between the seal and the rock mass (figures 5-6). Plasticisation zones in the vicinity of the culvert (the steel pipe), have only formed at the pressure applied on the isolating and retaining seal of 2.0 MN/m² and have increased in the subsequent calculation variant (figures 7-8). The maximal range of the plasticisation zones has not exceeded 25 cm from the culvert wall in case of the variant with the highest load of 3.2 MN/m². The calculated plasticisation of the material of the seal in concern for the load of 3.2 MN/m² has exhibited the usability of the designed isolating and retaining seal structure.

4. Calculation-based construction guidelines for the isolating and retaining seal with a culvert

4.1. Assessment of the possibility of reception of the hydrostatic pressures of the binding material by the steel culvert

The binding material used in the construction of the isolating and retaining seal with a culvert is a Binham plastic, which exerts hydrostatic pressure on the steel culvert during binding. During that time, the culvert constitutes an internal formwork.

According to Euler, at a uniform load ($p_{max} = p_{min} = q$), the slenderness ratio of the steel ring with the diameter of 2.0 m and the assumed wall thickness of 0.005 m, amounts to

$$\lambda = 2 \cdot \pi \cdot \frac{R}{g} = 1257 \gg 250 \quad (3)$$

where:

R – culvert ring radius, m,

g – thickness of the culvert wall, m.

Such a high slenderness ratio of the culvert ring eliminates the possibility of its full submersion in water or the fluidized binding material, which indicates the necessity to apply a technology where the isolating and retaining seal would be successively built by applying horizontal layers with a thickness depending on the strength of the wall of the steel culvert pipe [5].

4.2. Determination of the height of the technological layers of the binding material applied in the isolating and retaining seal

While building the isolating and retaining seal with subsequent horizontal layers, the wall of the culvert pipe will operate as yet another fragment of the cylindrical surface under an external load. To simplify, it may be assumed that due to the setting of the binding material, the radial interactions at the contact surface of the seal and the steel formwork (culvert) will disappear. Changes in the locations of the analysed fragments of the culvert wall indicate the variability of the static schemes of the steel coat. When building the lowest layer of the seal, encompassing the bottom of the steel pipe, the hydrostatic pressures will cause hydrostatic lift resulting in the necessity to bolt the culvert to the floor of the working, while the condition should be fulfilled

$$n \cdot k + G_R > W \quad (4)$$

where:

W – hydrostatic lift MN,

$$W = F_w \cdot R \cdot L$$

n – number of bolts for fixing the culvert to the floor,

k – load bearing capacity of a single bolt,

G_R – self-weight of the pipe, MN,

F_w – area of the part of the cross-section of the culvert pipe submerged in the fluidized binding material of the lower part of the seal, m²,

R – culvert pipe radius, m,

L – length of the section of the culvert pipe submerged in the fluidized binding material, m.

At the height of the first layer of the binding material of 0.3 m, the hydraulic lift will exert the following pressure on the pipe-wall

$$q_{max} = 0,3 \text{ m} \cdot \frac{20 \text{ kN}}{\text{m}^3} = 6,0 \text{ kN/m}^2 \quad (5)$$

For a section of the pipe with a width of 0,01 m, this means the need to transmit a uniform load to the bracing of the pipe amounting to

$$p = q_{max} \cdot 0.01 = 0.06 \text{ kN/m} \quad (6)$$

The heights of the technological layers of the binding material of the isolating and retaining seal should be determined based on the calculations:

- of the stability of the steel pipe at the maximal hydrostatic lift (for the lower layer of the binding material);

- verifying the reception of loads by fragments of the pipe located in each of the technological layers of the binding material;
- of the required load bearing capacity of the last layer of binding material over the culvert.

5. Conclusions

Where it is not possible to isolate flooded workings of a liquidated mine by installing water stoppings or full isolating and retaining seals, the construction of isolating and retaining seals with a culvert may be considered a solution. In such cases, the construction of the isolating and retaining seal with a culvert allows to achieve a protection against uncontrolled flow of water from the post-exploitation goafs to the water drainage working.

The presented method of calculating the values pertaining to the isolating and retaining seal with a steel culvert allows for the selection of the required length of the seal and the strength of the binding material, depending on the maximal expected water pressure. The application of the pipe culvert allows for controlled flow of water and air through the seal while protecting the drainage working against uncontrolled ingress of water accumulated in the adjacent post-exploitation workings.

The technology of execution of the isolating and retaining seal with a culvert should take into consideration the hydrostatic pressure exerted by the binding material with the qualities of Bingham plastic during the construction of the seal. Until the setting of the binding material, the plastic will cause hydrostatic pressure on the wall of the culvert, which – at that moment – serves as an internal formwork. Due to that, the technological thicknesses of the binding material applied in the seal should be specified based on static analyses of the culvert pipe with consideration given to the setting time of the binding material.

6. References

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