ГИАБ. Горный информационно-аналитический бюллетень /
MIAB. Mining Informational and Analytical Bulletin, 2022;(10-1):136–144
ОРИГИНАЛЬНАЯ СТАТЬЯ / ORIGINAL PAPER

УДК 622 DOI: 10.25018/0236_1493_2022_101_0_136

КОНСТРУКЦИИ ПОДАТЛИВЫХ КРЕПЕЙ В СОЛЯНЫХ ПОРОДАХ

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Аннотация: Строительство горных выработок в соляных породах на большой глубине осложняется непрерывным развитием деформаций породного контура. С увеличением размера поперечного сечения камеры величина деформаций тоже увеличивается. При строительстве камер большого поперечного сечения на больших глубинах ожидаются деформации породного контура, превышающие 1 м. Ввиду того, что напряжения, возникающие в крепи, превышают предел прочности материала, необходимо разработать конструкцию податливой крепи, способной выдержать нагружение. В работе приведена конструкция податливой крепи для камеры большого поперечного сечения, сооружаемой в соляных породах на глубине более 1 км.

Ключевые слова: соляные породы, глубокое заложение, податливое крепление, численное моделирование, пенобетон, большое поперечное сечение.

Для цитирования: *Дементьева А. В., Карасев М. А.* Конструкции податливых крепей в соляных породах // Горный информационно-аналитический бюллетень. – 2022. – № 10-1. – С. 136–144. DOI: 10.25018/0236_1493_2022_101_0_136.

Design of yielding support systems in salts

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Abstract: Construction of deep mines in salts is complicated by the fact that the excavation boundary deforms constantly during the whole operational period. The deformations of the mine boundary also decrease as the size of the excavation decreases. The most complicated case is a large deep excavation in salts because the expected deformations are more than 1 m. Conventional support cannot ensure the workability of the excavation because the stresses acting in the support are much higher than the strength of the support material. It is necessary to develop a special yielding support, that can withstand the load during the entire service life of the excavation. The design of yielding support for a large deep excavation in salts is given.

Key words: salt, deep mine, yielding support, numerical modelling, foam concrete, big cross-section.

For citation: Dementyeva A. V., Karasev M. A. Design of yielding support systems in salts. *MIAB. Mining Inf. Anal. Bull.* 2022;(10-1):136–144. [In Russ]. DOI: 10.25018/0236_1493_2022_101_0_136.

1. Introduction

The physical and mechanical properties of salt rocks cause problems in mine construction. The salts are prone to creep, so large deformations occur in the rock mass with a constant stress level [1–3]. Large deformations during the construction of deep mines occur due to overstressing rock. After excavation, the stresses in the rock mass increase more than its strength. If the process rate is low, creep deformations occur [4]. Salt creep does not decrease in time and causes large deformations of the excavation boundary with increasing depth. The role of ground support is to accommodate salt back displacement in a controlled manner rather than to prevent it entirely [5]. Such displacements must be taken into account in the design, and special measures during mining operations must be taken into account [6]. It is important to make a prognosis from the geomechanics point of view to prevent a support damage [7].

Shallow mines can be supported with expansion or screw-threaded anchors [8]. Such measures extend the operation period of the mine but are not effective in deep mines.

There are two other types of support in salt rocks: rigid or yielding mine support. The properties of a rigid support are designed to withstand the stresses of overburden, so the life cycle of the support depends on the material strength. Yielding supports reduce rock pressure with increasing deformations, because they have flexible elements in them.

There is no possibility of deformation in a rigid support, so the stresses greatly exceed the strength of the material and damage the support. Stresses in a yielding support do not reach the strength limit, although there are large deformations of the excavation boundary. Stresses are smaller as there is no direct dependence between stresses and displacements [9].

Different support designs determine the mechanism of deformations in the yielding support. The main support principle is to dissipate energy of deformation [10] and decrease the stress level. One of the ways to design a yielding support is to place a compressible layer between the rigid lining and the excavation boundary. When the excavation boundary is deformed, the layer is compressed without deformation of the lining [11]. Such a compressible layer can be made of steel cylinders located between the rock mass and the roof beam. Since the diameter of the cylinder should be 1.5 — 2 times larger than the expected deformations of the excavation boundary[8], such a design is more difficult to perform in the areas with creep deformations.

Another design is a support that interacts with the rock mass. The ductile elements are embedded in the concrete lining, and the convergence of cross-section is ensured by the radial displacements of the lining, which deforms during compression of the ductile elements without losing stability and exceeding the strength of the material [12,13]. The ductile elements can work both in friction elements (the supporting elements are connected by friction-prop locks and can slide relative to each other) and in compression elements (highly compressive elements are included in the design of the supports) [13,14].

The material of the ductile elements depends on the expected displacements of the excavation boundary. The rigid shell during construction is divided into segments with open gaps in it. These gaps are filled with highly compressible elements. The rigid material is usually shotcrete, and the ductile material is steel, timber, ash-slag [15] or foamed materials (foamed concrete) [16–18].

Foamed concrete is a lightweight concrete with a mass density of 800 — 1500 kg/m^3 that can vary depends on number of air-voids [19]. Compared to shotcrete, foamed concrete can have a certain compressive strength and good ductility, which allows it to be used as a ductile material in yielding supports [20]. In addition, foam concrete compressive strength can be changed both by changing dry density, water/cement ratio and cement type [21] and by adding some filler such as polymer fiber or ceramsite [22].

Although the specimens are usually tested under compressive or compression load, as the most suitable to the future operation conditions[23], foamed concrete is not prone to brittle failure. The deformation curve of foamed concrete can be divided into 4 significant stages: elastic stage, plastic stage with peak stress at the end, post-peak strain softening, residual deformations[24,25]. Foamed concrete passes through all stages during its life cycle as a ductile element in a yielding support.

2. Rock mechanics model

A large cross section chamber located in the salt rocks at a depth of 1 km depth was chosen as a rock mechanic model. Rock mechanics modelling was performed in the Abaqus CAE program, where finite elements calculations are executed. A large chamber is constructed in 100 m thick salt rock and surrounded by primary rocks. The size of the chamber should be 20*12 m to ensure the operational safety.

The size of the cross section of the mine is usually chosen in connection with the construction technology. As the mine becomes deeper and continuous salt deformations must be taken into consideration, the technological has less influence on the choice of size. The choice is based on the expected stresses and deformations of the mine as they are more valuable for deep mining. The cross-sectional size remains roughly constant to accommodate the equipment, but the shape is changed to elliptical or horseshoe-shaped to avoid stress concentrators (Fig. 1).

The support is made in the form of a shotcrete shell with open slots. The slots are filled with highly compressible foamed concrete elements. Such a support can operate in two modes — in rigid or yielding mode. In the rigid mode, the bearing capacity depends on the strength of shotcrete, and the deformation properties of foamed concrete determine the yielding mode of the support.

The thickness of the shotcrete shell is 0,5 m. Foamed concrete elements are placed between the shotcrete elements with a certain experimentally found spacing (Fig. 2). In the horseshoe cross-section, the size of the ductile elements is 0.4 m. For the elliptical cross-section, the size is increased to 0.5 m, which allows to increase the spacing and reduce the number of elements.

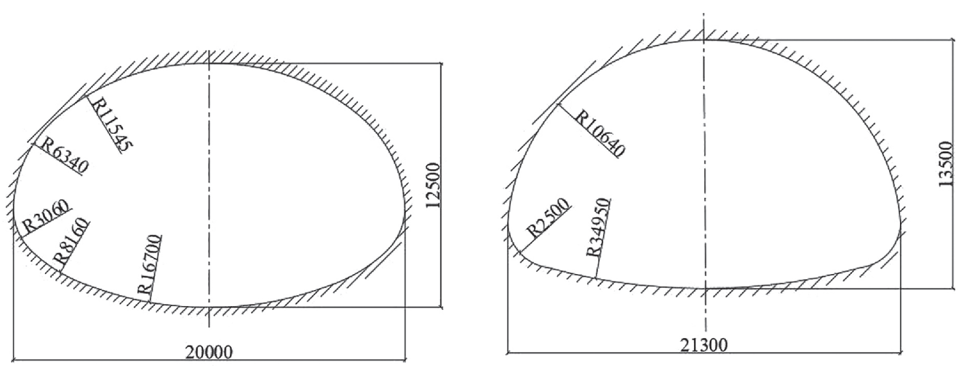


Fig. 1. Cross sections of the chambers

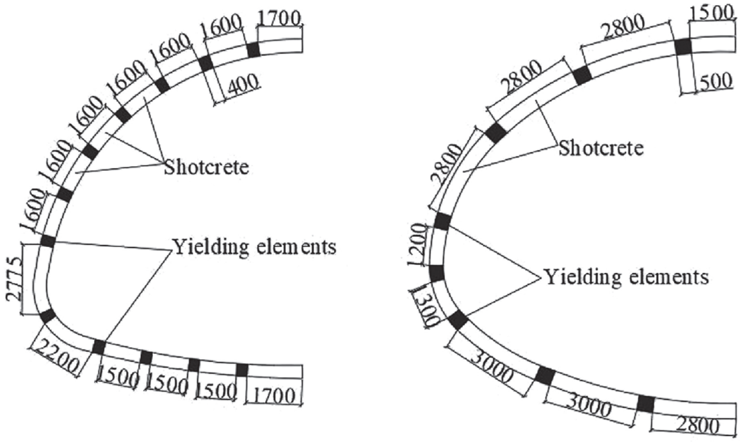


Fig. 2. Distance between ductile elements

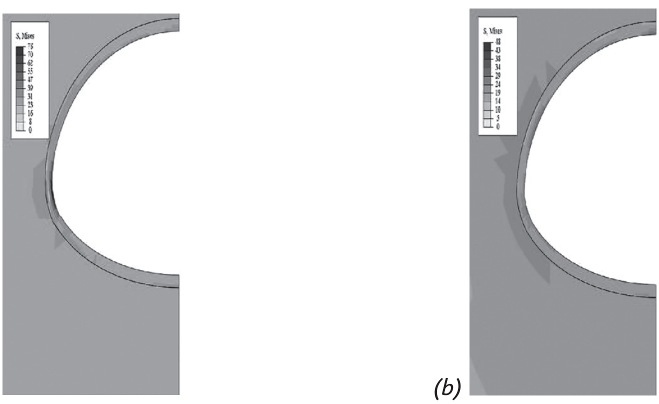
It is found that the yielding element should be placed in stress concentration zones. Such zones are the arch and inversion conjunctions in the horseshoe section and in the elliptical sidewall. The distance between them makes it possible to avoid stresses in the shotcrete shell exceeding the strength. (Fig. 3).

To compare the two support principles, the rigid support is modelled as a 0.5 m diameter shotcrete shell.

To adjust the parameters and verify the model, the deformations of the mine workings boundaries in the model were compared with the deformations of the mine workings boundaries in previously constructed mines.

The Creep – Power Law model is used to determine the long-term behavior of the salt rock. The model approximates creep behavior using a power law. To adjust the parameter and verify the model, the deformations of the excavation boundaries in the model were compared with the deformations of the excavation boundaries in the previously constructed mines.

$$\dot{\varepsilon}^{cr} = \dot{\varepsilon}_0 \left[\left(\frac{\bar{q}}{q_0} \right)^n \left[(m+1)\bar{\varepsilon}^{cr} \right]^m \right]^{\frac{1}{m+1}},$$



(a) *(b)*

Fig. 3. Stresses in the yielding support (a) without and (b) with yielding element in the side wall

Table 1
Parameters of the salt model

q_0	n	m	ε_0
245	3	–0.43	1

where $\dot{\varepsilon}_0$, q_0, n, m are the material parameters.

The shotcrete shell is defined as an elastic material with the assignment of Poisson's ratio and Young's modulus.

Foamed concrete elements are specified by the model of the crushable foam model with deviator hardening. The model is based on the yield surface, which is described by the elliptic dependence of deviator stress on pressure. The surface change is due to volumetric plastic deformations.

The crushable foam model is endowed with parameters that describe the yield surface. The surface expands with the accumulation of volumetric strain, and the material hardens.

$$F = \sqrt{q^2 + \alpha^2 (p - p_0)} - B,$$

$$p = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

$$B = \alpha \cdot \frac{p_c + p_t}{2},$$

$$p_0 = \frac{p_c - p_t}{2}.$$

The crushable foam model correctly describes the behavior of the foamed concrete under load. The model is calibrated using the compression tests diagrams [1]. The compression test is accurately modelled in Abaqus CAE. To simplify the model, peak stress is excluded from the diagram (the diagram is smoothed) and it is assumed that the material deforms plastically without reaching the maximum load value.

The parameters calculated from the model are compared with those from the compression tests. The diagram (Fig. 4) shows that there is a good correlation.

3. Abaqus CAE modelling

The problem is solved in the plane strain mode. The initial stress field is offset to 25 MPa. The upper part of the model, which simulates overburden rocks, is under load. The load is 25 MPa. The vertical boundaries of the model are constrained from horizontal displacements and the bottom boundary is constrained from vertical displacements.

The interaction of the support and the rock mass occurs in the tangential direction. The value of the friction coefficient is 0.03

The interaction of the support and the rock mass occurs in the tangential direction. The value of the friction coefficient is 0.03.

The model is meshed on finite elements. The salt rock is meshed on triangular elements of quadratic order, and the size of the elements decreases near the boundary of the excavation. The mesh density is increased until further increases result in no effect on the calculation results.

The support is meshed on quadratic elements of linear order. To improve the convergence of the problem, the shotcrete elements are assigned as incompatible modes and the foamed concrete elements are assigned as reduced integration. Foamed concrete elements are meshed on finite elements with dimensions equal to those of yielding elements in the direction of the maximum force.

The calculations are executed in two steps. In the first step, all loads are introduced, and in the second step, the long-term behavior of the salt is modelled. The visco-plastic behavior of the salt is performed using the Visco procedure. The

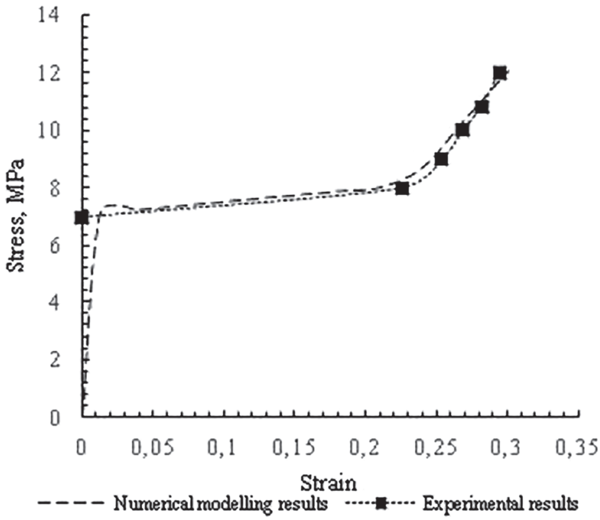


Fig. 4. Verification of the crushable foam model

time period is set for 18250 units. This equals to 18250 days (50 years).

4. Results

To present the results, displacements and stresses were obtained at the top heading and the side wall points.

In the rigid support, the stresses are 10 times higher than the strength of the shotcrete at the end of its service life. In the elliptical cross-section, stresses reach 214 MPa in the top heading and 150 MPa in the side wall point. In the horseshoe section, stresses reach 242 MPa and 170 MPa, respectively (Fig. 5). The compressive strength of shotcrete is achieved in the first 5 years, and further operation destroys the lining. That is why rigid supports cannot be used in deep salt mines.

The stresses acting in the yielding support are lower than the strength of the shotcrete throughout its service life. In the horseshoe-shaped cross-section, high stresses are observed in the sidewall. At the end of the service life they are 15.7 MPa, while in the top heading they are 2.5 MPa. Stresses in the elliptical cross-section are higher than in the horseshoe one. At the end of svc life, they are 21.6 MPa in the top heading and 15.4 MPa in the sidewall, which is close to the stresses in the horseshoe section sidewall.

The deformations of the excavation boundary are not constant across the cross-section. At the end of the service life, the vertical displacements of the top heading of the excavation are 1.06 m for horseshoe cross-section and 1.03 m for the elliptical cross-section (Fig. 7). Horizontal displacements tend to zero during the operational life, so the top heading moves only vertically. The displacements of the elliptical cross-section sidewall are larger than those of the horseshoe cross-section and reach a value of 0.74 m, while the displacements of the horseshoe cross section are 0.61 m.

5. Conclusion

Rigid supports cannot be used in a deep salt mine, although rigid supports are commonly used in rocks that are prone to creep. As a result of numerical modelling, the rigid support cannot withstand the load and endure the workability of the chamber. The strength of shotcrete is achieved in

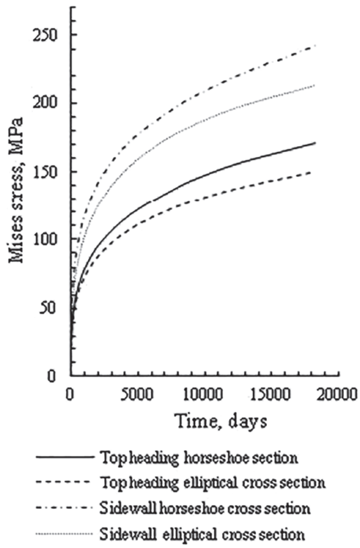


Fig. 5. Rigid support stress conditions

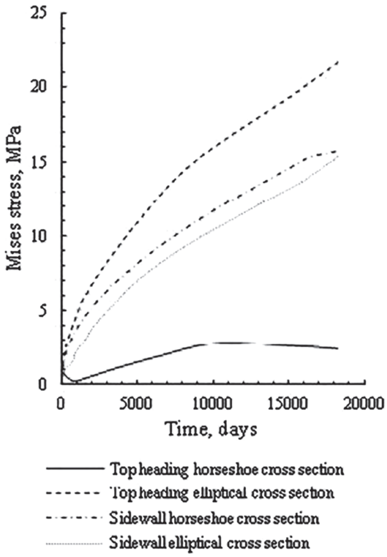


Fig. 6. Yielding support stress conditions

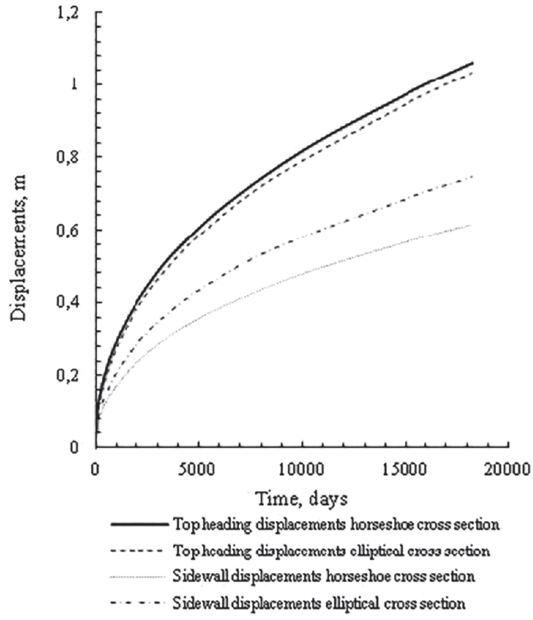


Fig. 7. Displacements of the yielding support during the service life

the first five years, so it is necessary to take special measures for reinforcement. Therefore, for a large cross-section chamber at a depth of 1 km in salt mines, a yielding support should be used. The design of such support is a combination of shotcrete and foamed concrete elements, so their relative position is determined experimentally. Such a support reduces the deformation of the excavation boundary, and the stresses acting in the support are lower than the strength of the material during the entire service life.

The stress state of the support depends on the number of foamed concrete elements and the distance between them. At the points of stress concentration points (sidewall points) ductile elements must be installed to avoid overloading and damage to the shotcrete.

Meanwhile, the use of highly compressible elements creates stability loss problems because the ductile elements will lose their performance.

The properties of the foamed concrete must be assigned so as to avoid the additive destructive effects on the shotcrete elements. The stresses accumulated in the foamed concrete must be below the strength of the shotcrete. Meanwhile, the use of highly compressible elements creates the stability loss problems as ductile elements will lose their performance.

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ИНФОРМАЦИЯ ОБ АВТОРАХ

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Получена редакцией 20.03.2022; получена после рецензии 27.06.2022; принята к печати 10.09.2022.
Received by the editors 20.03.2022; received after the review 27.06.2022; accepted for printing 10.09.2022.