

Development and substantiation of vertical shaft lining designs under complex mining-geological and hydrogeological conditions

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Abstract

Purpose. Development and substantiation of an injection-grouting technology for stabilising an aquifer during vertical shaft sinking in a serpentinite rock mass containing alkaline, magnesium-bearing groundwater that limits the effectiveness of conventional cement grouting.

Methods. The study included an analysis of the geochemical conditions of water-bearing sublayer IV-4 at the 10th Anniversary of Kazakhstan's Independence Mine and determination of the geochemical aggressiveness factor K_{gc} ; laboratory testing of two two-component polyacrylate grouts on consolidated serpentinite specimens with a particle size of 0.5-3.0 mm in a water-saturated alkaline environment at pH = 10; microscopic analysis of the polymerisation process; uniaxial compression testing using a GCTS ULT-200 press; and finite element modelling in Rocscience RS3 for the rock mass before and after injection grouting.

Findings. The geochemical conditions of the aquifer, characterised by pH = 9-11 and the presence of Mg^{2+} and HCO_3^- ions and dissolved SiO_2 , limit the use of Portland cement because of magnesium-induced corrosion. The factor $K_{gc} = 0.118$ represents an 8.5-fold reduction in the load-bearing capacity of the serpentinite rock mass after water saturation. The strength of specimens prepared with the first polyacrylate grout reached 6.1 MPa at $K_{str} = 2.68$, which was 61 times higher than that of specimens prepared with the second grout. Numerical modelling showed that the minimum SF increased from 0.50 to 0.67 and the maximum from 2.85 to 3.83, with a zone of improved stability forming around the shaft.

Originality. The combined use of the K_{gc} and K_{str} factors was substantiated for assessing geochemical effects and the effectiveness of serpentinite rock mass strengthening. The interaction of polyacrylate gel with Mg^{2+} ions was interpreted through the formation of $(-COO)_2Mg$ coordination complexes.

Practical implications. An injection-grouting scheme was proposed for stabilising the aquifer through 25.0 m long boreholes drilled at an angle of 5°, forming a 0.75 m thick grouted rock zone around the shaft. The use of polyacrylate grout improves the stability of the water-saturated serpentinite rock mass, reduces the likelihood of groundwater inflow pathways, and provides safer conditions for vertical shaft sinking. The proposed technology can be used in mine shaft construction under similar mining-geological and hydrogeological conditions.

Keywords: mine shaft; aquifer; serpentinite; polyacrylate gel; injection grouting; strengthening factor; numerical modelling

1. Introduction

Vertical mine shafts are key components of underground mining infrastructure. They connect underground workings with the surface and provide access for transporting ore and personnel, ventilation, and mine water drainage. The reliability and service life of mine shafts largely determine the overall efficiency of a mining operation, since damage to the shaft lining or the loss of shaft functionality may cause prolonged downtime and significant economic losses [1], [2]. Therefore, maintaining the stability of vertical shafts throughout their construction and operation remains a priority in mining engineering. Global experience indicates that vertical shaft construction accounts for approximately 30% of the total cost and up to 50% of the overall duration of

mine construction, while shaft lining installation represents up to 60% of these costs [3]. Improvements in vertical shaft construction are associated with the mechanisation of shaft-sinking operations, increased reliability of mine hoisting systems, and the electrical safety of equipment. Progress in these areas reduces labour requirements and improves the safety of shaft operations [4]-[6].

The efficiency of underground excavation also depends on improvements in drilling and blasting operations and the service life of shaft-sinking tools [7]. Sectional blasting enables more efficient formation of cut cavities [8], while improved manufacturing methods for drill-bit teeth and the use of wear-resistant hardfacing and thermite alloys increase the durability of equipment components [9]-[13].

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A characteristic trend in the modern mining industry is the gradual increase in mining depth. As mining operations advance to deeper levels, rock pressure, temperature, and water inflow increase, making the construction and operation of vertical shafts considerably more challenging. The most difficult sections are those that intersect zones of unstable and water-saturated rocks with low strength and deformation characteristics. Under such conditions, conventional support methods developed mainly for relatively stable rock masses do not always provide the required lining reliability throughout the entire service life of the shaft [14].

Maintaining the stability of engineered mining structures in disturbed rock masses requires an integrated assessment of deformation processes, support parameters, and geomechanical monitoring results [15]. International experience shows that more than half of the surveyed mine shafts at deep levels have lining damage of varying severity, confirming the importance of this problem [16], [17].

The chromite deposits of the Kempirsai Massif in Kazakhstan, which are developed by the mines of the Donskoy Mining and Processing Plant, are notable for their complex mining-geological conditions. The deposits are located near the town of Khromtau in the Aktobe Region of the Republic of Kazakhstan and contain some of the world's largest chromite ore reserves. The balance reserves of the ore field in categories B + C amount to approximately 100 million tonnes. The ore bodies occur at depths ranging from 300 to 1500 m and form large lens- and vein-shaped structures, some of which contain reserves of up to 60 million tonnes. They are hosted by ultrabasic rocks, mainly serpentinites and gabbro-amphibolites, which have specific physical and mechanical properties. The rock mass is characterised by numerous tectonic faults, extensive fracturing, and a hierarchical block structure, with an average structural block size ranging from 0.05 to 1.0 m. A quantitative assessment of fracture parameters and the spatial orientation of structural discontinuities is essential for developing reliable geomechanical models of the rock mass.

When saturated with water, serpentinite strength decreases significantly: the internal friction angle declines from 35-40 to 17-20°, while cohesion decreases from 4-6 to 0.8-1.5 MPa. This results in higher loads on the support systems of underground workings [18], [19]. Under such conditions, the support design should be selected with consideration of the local geomechanical and hydrogeological characteristics of the rock mass [20]. The reliability of geomechanical assessment depends on the quality of geological and geophysical data processing and their spatial integration. For this purpose, optimisation methods for processing gravimetric data, geographic information systems, and three-dimensional modelling of mining structures are used [21]-[24].

The experience of vertical shaft construction at the 10th Anniversary of Kazakhstan's Independence Mine clearly demonstrates the complexity of this problem. In five mine shafts, lining stresses reached the compressive strength of concrete at depths below 500 m. Cracks and lining deformations were recorded in the cage shaft and the skip-and-cage shaft. The most serious failure occurred in the cage shaft, where approximately 200 m of concrete lining was completely destroyed within the depth interval of 552-765 m. The repair work lasted more than two years. The damaged concrete lining was replaced with a type 85N tubbing lining

with a back-plate thickness of 40 mm, while the space behind the lining was filled with class B15 concrete. However, after shaft sinking resumed, horizontal tensile cracks developed in the tubbing lining. These deformations were associated with the transition of the rock mass to an inelastic state and the displacement of structural blocks under high stresses. These circumstances required special studies to develop a reliable lining design for the Skipovoy shaft, which has a planned depth of 1200 m [25]. Geomechanical risks are assessed using numerical modelling, spatial mapping, and instrumental monitoring of deformations. These methods help identify potentially unstable sections of the rock mass and predict the development of deformation processes [26], [27].

The most challenging stage in the construction of the Skipovoy shaft is its intersection with the water-saturated IV-4 stratum at depths of 1040-1057 m. The combination of extensive fracturing, the reduced strength of water-saturated serpentinites, and the considerable predicted water inflow requires preliminary grouting of the rock mass. The grout must not only improve rock mass stability and reduce water flow but also retain its properties under prolonged exposure to alkaline, magnesium-bearing groundwater.

A conventional method for isolating aquifers during vertical shaft sinking is advance cement grouting from the shaft bottom with the construction of a grouting pad. The effectiveness of this method depends not only on the properties of the grouting material but also on the quality of filling behind the lining, the continuity of the cemented layer, and the technological risks associated with the grouting process [28]. However, the application of this method in serpentinite rock masses is subject to geochemical limitations. Groundwater in these rock masses is formed during the serpentinitisation of ultrabasic rocks and is characterised by an alkaline reaction and elevated concentrations of Mg^{2+} and HCO_3^- ions and dissolved SiO_2 . In magnesium-rich environments, Portland cement may undergo magnesium-induced corrosion. Mg^{2+} ions react with the hydrated phases of the hardened cement paste, producing loose and unstable brucite, $Mg(OH)_2$. This process gradually reduces the strength and waterproofing properties of the grouting material [29], [30]. An additional challenge is the presence of talc minerals in fracture fillings, whose surfaces do not provide reliable adhesion to cement grout, as reported in previous studies [31], [32]. The effectiveness of grouting also depends on the injectability of the rock mass, the stability of grout flow, and the ability of the injection channels to remain permeable. In related geotechnological processes, grout activation, well declogging, and the regeneration of process wells are used for this purpose [33]-[38]. The selection of operating parameters should therefore be treated as a comprehensive optimisation problem that links the characteristics of the underground system, the parameters of surface equipment, and the technological constraints of the process [39], [40].

In recent years, polymer-based chemical grouts have been increasingly used in mine construction [41]. Comparative studies of cement and polymer grouting show that epoxy- and polyurethane-based materials can provide stronger adhesion to fracture surfaces than conventional cement grouts. Studies of acrylate and polyacrylate compounds have confirmed their resistance to alkaline environments and their ability to form a waterproof, elastic gel directly within a water-saturated rock mass [42], [43]. The low viscosity of

acrylate gels, approximately 1-2 mPa·s, allows them to penetrate microcracks less than 0.05 mm wide, which are inaccessible to most cement grouts [44]. The geomechanical interaction between support systems and disturbed rock masses under different support arrangements has also been examined in several studies [45], [46]. Numerical modelling of the stress-strain state, taking into account rock mass fracturing, the physical and mechanical properties of the rocks, and mining parameters, is widely used to assess the geomechanical condition of disturbed rock masses [47], [48].

Modern mining technologies are also assessed in terms of resource efficiency and environmental safety. Current research addresses resource recovery from mining waste, the use of technogenic raw materials in mineral binders, drilling waste treatment, and the assessment of soil contamination in mining areas [49]-[53].

However, the selection of grouting materials based on the geochemical properties of groundwater in serpentinite rock masses remains insufficiently studied. In particular, little research has examined the compatibility of grouting materials with alkaline, magnesium-bearing groundwater or their interaction with serpentinite and talc-bearing fracture surfaces under deep-shaft conditions. The parameters of the grouted rock zone and their influence on the stability of the rock mass surrounding the shaft also remain insufficiently justified. The lack of comprehensive recommendations for selecting suitable grouting materials and determining the design parameters of rock mass grouting highlights the relevance of this study.

This study aims to develop and substantiate differentiated lining designs for the Skipovoy shaft of the 10th Anniversary of Kazakhstan's Independence Mine within the depth interval of 900-1200 m, considering the geomechanical characteristics of individual rock strata. It also aims to justify the use of a chemical grout for stabilising the water-saturated stratum based on an analysis of geochemical conditions, laboratory testing of grouting materials, and numerical modelling of the proposed technology.

2. Methods

The study focuses on the Skipovoy vertical shaft of the 10th Anniversary of Kazakhstan's Independence Mine (DNK Mine), operated by the Donskoy Mining and Processing Plant. The shaft is being constructed to a design depth of 1200 m. Within the studied depth interval of 900-1200 m, the shaft intersects a sequence of ultrabasic rocks that differ considerably in lithological composition, degree of distur-

bance, and hydrogeological conditions. Based on engineering-geological investigation data from shaft pilot borehole No. 5-KS, six main rock strata were identified within this interval. These strata differ significantly in their physical and mechanical properties, stability categories, and hydrogeological characteristics (Fig. 1).

The fourth layer is of particular importance because it contains a 17 m thick aquifer at depths of 1040-1057 m. The hydraulic conductivity within this aquifer is $k_f = 0.025$ m/day, which is several times higher than the average value for the surrounding rock mass. Without advance grouting, the total predicted water inflow into the shaft may reach 35 m³/h, while inflow from individual zones ranges from 2.0 to 3.5 m³/h. The clear internal diameter of the shaft is $D = 8.0$ m, and a combined shaft-sinking method is used. When the shaft intersects the aquifer, its lining is subjected to the combined pressure of the surrounding rocks and groundwater, with a design value of 1.16-1.32 MPa [25], [54].

The upper part of the geological section, extending to a depth of 927 m (layer I), consists of moderately to slightly fractured gabbro-amphibolites with a compressive strength of $\sigma_c = 42.5$ MPa and a deformation modulus of $E = 15.0$ GPa. Below this, at depths of 927-943.2 m (layer II), highly fragmented serpentinites occur. These rocks have considerably lower strength properties, with $\sigma_c = 2.28$ MPa and an internal friction angle of $\varphi = 25^\circ$. Layer III (943.2-983 m) consists of moderately fractured serpentinites with $\sigma_c = 24.6$ MPa.

Layer IV (983-1065.8 m) is the most complex and heterogeneous part of the section. It is divided into five sublayers (IV-1-IV-5), which differ considerably in their degree of fracturing, strength properties, and hydrogeological characteristics. Sublayer IV-4 (1040-1057 m) is particularly important because it represents a 17 m thick water-saturated zone with a hydraulic conductivity of $k_f = 0.025$ m/day. Layers V (1065.8-1136.1 m) and VI (1136.1-1200 m) consist of slightly fractured serpentinites with compressive strengths of $\sigma_c = 30.68$ and 39.1 MPa, respectively. The physical and mechanical properties of the rocks in all layers are presented in Table 1.

To assess rock mass stability within the studied interval, an integrated approach involving two independent methods was used. The first method was the Mining Rock Mass Rating (MRMR) classification developed by D. Laubscher [55]. This method assesses the rock mass rating by considering the strength of rock blocks, fracture density and condition, as well as adjustment factors for weathering, joint orientation, blasting operations, and water inflow.

Table 1. Physical and mechanical properties of rocks within the shaft depth interval of 900-1200 m

Layer No.	H , m	σ_c , MPa	φ , degrees	E , GPa	ν	Weakening coefficient
I	900-927	42.48	41	15.0	0.29	0.6
II	927-943.2	2.28	25	7.0	0.31	0.2
III	943.2-983	24.6	33	9.0	0.31	0.4
IV-1	983-1024.3	28.0	35	10.0	0.31	0.4
IV-2	1024.3-1028.6	14.0	35	10.0	0.31	0.2
IV-3	1028.6-1040	19.6	35	10.0	0.31	0.4
IV-4	1040-1057	19.6	35	10.0	0.31	0.28
IV-5	1057-1065.8	28.0	35	10.0	0.31	0.4
V	1065.8-1136.1	30.68	40	14.0	0.30	0.4
VI	1136.1-1200	39.1	36	12.0	0.29	0.5

Layer No.		Depth, m	Absolute level scale	Thickness of the engineering geological unit	Description of the engineering geological unit	Rock mass fragmentation map	Lithological column
I		900	-513.5	$H = 900$ m	Medium-weakly cracked gabbro amphibolites. In the ranges 911.8-922.5 m – amphibolites; in the range 911.8-927.0 m – amphibolite serpentinites. The rocks have a massive texture, with the exception of the interval 911.8-927.0 m, where they are shale. Quartz-siliceous filler along the cracks. Pyritization is marked on the walls of cracks. Crack thickness ranges from fractions of 1-2 mm.		LLLLLL
		905	-518.5	$H = 927$ m			LLLLLL
		910	-523.5				LLLLLL
		915	-528.5				LLLLLL
		920	-533.5				VVVVVVVV
		925	-538.5				VVVVVVVV
II		930	-543.5	$H = 943.2$ m	Fragmented serpentines. Serpentines are apopyroxenitic, antigoritic fragmented. The cracks are filled with serpophyte filler. Crack thickness ranges from fractions of 1-5 mm		SSSSSSS
		935	-548.5				SSSSSSS
		940	-553.5				SSSSSSS
III		945	-558.5	$H = 983$ m	Medium-cracked serpentines. Serpentines according to peridotite, hornblende peridotite. The rocks have a massive texture and are intensely fractured. Seopophyte filler is marked along the cracks. The crack thickness ranges from fractions of 1-3, 1-5 mm.		SSSSSSS
		950	-563.5				SSSSSSS
		955	-568.5				SSSSSSS
		960	-573.5				SSSSSSS
		965	-578.5				SSSSSSS
		970	-583.5				SSSSSSS
		975	-588.5				SSSSSSS
		980	-593.3				SSSSSSS
IV-1		985	-598.5	$H = 1024.3$ m	Medium-cracked serpentines. In the range 983.0-1028.6 m – serpentines of pyroxene peridotite and peridotite; in the range 1028.6-1057.6 m – apopyroxene serpentinites (1040-1057 m heavily watered); in the range 1057.6-1065.8 m – apodunite serpentines. The rocks are mostly of massive texture, with the exception of the interval 1024.3-1028.6 m, where they are cataclysmic and fractured. The cracks are filled with serpophyte and serpentine filler. The crack thickness ranges from fractions of 1-3 mm.		SSSSSSS
		990	-603.5				SSSSSSS
		995	-608.5				SSSSSSS
		1000	-613.5				SSSSSSS
		1005	-618.5				TSITSISIS
		1010	-623.5				SSSSSSS
IV-2		1015	-628.5	$H = 1028.6$ m			SSSSSSS
		1020	-633.5				SSSSSSS
IV-3		1025	-638.5	$H = 1040$ m			SSSSSSS
		1030	-643.5				SSSSSSS
IV-4		1035	-648.5	$H = 1057$ m			Sn Sn Sn Sn
		1040	-653.5				Sn Sn Sn Sn
		1045	-658.5				Sn Sn Sn Sn
IV-5		1050	-663.5	$H = 1065.8$ m			Sn Sn Sn Sn
		1055	-668.5		Sa Sa Sa Sa		
		1060	-673.5		Sa Sa Sa Sa		
V		1065	-678.5	$H = 1036.1$ m	Slightly cracked serpentines. In the range of 1065.6-1080.5 m, there are serpentines of massive texture. In the ranges 1080.5-1107.0 m and 1124.0-1136.1m, the serpentines are apodunite of massive texture. In the range of 1107.0-1124 m, the serpentines are apopyroxene with a weakish texture. There are serpophyte and serpentine fillers along the cracks, and brown spots (crusts) of calcification are noted along the crack stacks. The crack thickness ranges from fractions of mm to 1-3 mm, and in the range of 1078.0-1115.3 m up to 5-6 mm.		SSSSSSS
		1070	-683.5				SSSSSSS
		1075	-688.5				Sa Sa Sa Sa
		1080	-693.5				Sa Sa Sa Sa
		1085	-698.5				Sa Sa Sa Sa
		1090	-703.5				Sa Sa Sa Sa
		1095	-708.5				Sa Sa Sa Sa
		1100	-713.5				Sa Sa Sa Sa
		1105	-718.5				Sn Sn Sn Sn
		1110	-723.5				Sn Sn Sn Sn
		1115	-728.5				Sn Sn Sn Sn
		1120	-733.5				Sa Sa Sa Sa
VI		1125	-738.5	$H = 1200$ m			Sa Sa Sa Sa
		1130	-743.5				Sa Sa Sa Sa
		1135	-748.5				Sa Sa Sa Sa
		1140	-753.5				Sa Sa Sa Sa
		1145	-758.5				Sn Sn Sn Sn
		1150	-763.5				Sn Sn Sn Sn
		1155	-768.5				Sa Sa Sa Sa
		1160	-773.5				Sa Sa Sa Sa
		1165	-778.5				Sa Sa Sa Sa
		1170	-783.5				Sa Sa Sa Sa
		1175	-788.5				Snp Snp Snp
		1180	-793.5				Snp Snp Snp
		1185	-798.5	$H = 1200$ m		Snp Snp Snp	
		1190	-803.5			Snp Snp Snp	
		1195	-808.5			Snp Snp Snp	
		1200	-813.5			Snp Snp Snp	
		1205	-818.5			Snp Snp Snp	
		1210	-823.5			Snp Snp Snp	
		1215	-828.5			Snp Snp Snp	

Figure 1. Stratigraphic column and engineering-geological description of rocks based on the geological section of borehole No. 5-KS within the shaft depth interval of 900-1200 m

The rock mass rating is calculated as follows:

$$MRMR = RMR \cdot A_w \cdot A_j \cdot A_b \cdot A_{gw}, \quad (1)$$

where:

RMR – basic rock mass rating ($RMR = R_{RBS} + J_S + J_C$);
 A_w – weathering adjustment factor;
 A_j – joint orientation adjustment factor;
 A_b – blasting adjustment factor;
 A_{gw} – groundwater inflow adjustment factor.

The second method was a code-based calculation of the horizontal radial load acting on the lining along the main shaft section, determined using the following expression [3]:

$$P_h = K_o \cdot K_u \cdot m_w \cdot K_{gc} \cdot P_n \cdot [1 + 0.1(r_0 - 3)], \quad (2)$$

where:

K_o – load factor (1.3);
 K_u – non-uniform load distribution factor;
 m_w – lining service-condition factor;
 P_n – standard horizontal load, kPa;
 r_0 – clear shaft radius, m;
 K_{gc} – geochemical aggressiveness factor.

The K_{gc} factor accounts for the reduction in serpentinite strength caused by water saturation and is determined as follows:

$$K_{gc} = \frac{\varphi_{wet} \cdot C_{wet}}{\varphi_{dry} \cdot C_{dry}}, \quad (3)$$

where:

φ_{wet} – internal friction angle of water-saturated rocks, degrees;
 C_{wet} – cohesion of water-saturated rocks, MPa;
 φ_{dry} – internal friction angle of dry rocks, degrees;
 C_{dry} – cohesion of dry rocks, MPa.

For the conditions of sublayer IV-4: $\varphi_{dry} = 35^\circ$; $C_{dry} = 5.0$ MPa; $\varphi_{wet} = 18^\circ$; $C_{wet} = 1.15$ MPa; $K_{gc} = 0.118$.

The use of two independent stability assessment methods allowed the results to be cross-checked and provided a more reliable understanding of the geomechanical condition of each rock layer. Based on the stability assessment, an individual lining design was developed for each layer. The load-bearing capacity of the monolithic concrete lining under uniform loading was determined using the strength condition for a thick-walled ring:

$$P_c = [\sigma_c] \cdot 0.5 \cdot \left[1 - \left(\frac{r_0}{r_0 + \delta} \right)^2 \right], \quad (4)$$

where:

$[\sigma_c]$ – allowable compressive stress of the lining material, MPa;
 δ – lining thickness, m.

The thickness of the monolithic concrete lining was calculated as follows:

$$\delta_l = m_w \cdot r_0 \cdot \left(\sqrt{\frac{m_{\sigma 1} \cdot m_{\sigma 3} \cdot m_{\sigma 7} \cdot R_c}{m_{\sigma 1} \cdot m_{\sigma 3} \cdot m_{\sigma 7} \cdot R_c - 2K_s \cdot P}} - 1 \right) - \delta_{sc}, \quad (5)$$

where:

R_c – design compressive strength of concrete, MPa;
 K_s – stress concentration factor;
 P – horizontal pressure acting on the lining, MPa;
 δ_{sc} – thickness of the rock-concrete composite shell, m.

For the aquifer in sublayer IV-4 at depths of 1040-1057 m, the total pressure acting on the lining was determined by considering both rock and hydrostatic pressures:

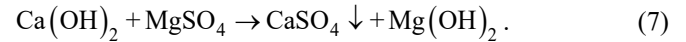
$$\Sigma P_t = (P_r + P_w) \cdot K_{cd}, \quad (6)$$

where:

P_r – rock pressure acting on the lining, MPa;
 P_w – hydrostatic pressure ($0.01 \cdot h = 0.17$ MPa);
 K_{cd} – long-term stability factor of the grout in an aggressive geochemical environment.

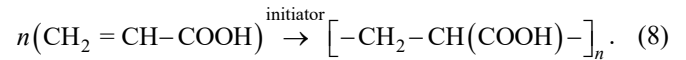
For Portland cement exposed to magnesium-bearing groundwater $K_{cd} > 1.0$, whereas for polyacrylate gel, $K_{cd} = 1.0$.

The conventional method for isolating aquifers during shaft sinking is advance cement grouting from the shaft bottom with the construction of a grouting pad. However, the geochemical conditions of the serpentinite aquifer at the DNK Mine make Portland cement unsuitable as a grouting material. The groundwater contains high concentrations of Mg^{2+} and HCO_3^- ions and has an elevated pH of 9-11 due to the active serpentinisation of ultrabasic rocks [54]. Under these conditions, Portland cement undergoes magnesium-induced corrosion according to the following reaction:



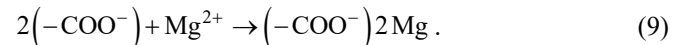
The resulting gypsum, $CaSO_4$, causes expansion and deterioration of the hardened cement paste, while loose brucite, $Mg(OH)_2$, has no binding properties. As a result, the hardened grout gradually deteriorates and loses its waterproofing properties. An additional challenge is the presence of talc minerals, $Mg_3Si_4O_{10}(OH)_2$, in the fracture fillings. Their surfaces are chemically inert and do not provide sufficient adhesion to cement grout.

Two polyacrylate injection grouts, each consisting of two components, were selected for the study. The first was a polyacrylate gel based on acrylic acid and its salts. It had a viscosity of 1-2 mPa·s and formed an elastic, waterproof polymer network with high resistance to alkaline environments after curing. Its main components were acrylic acid monomers, $CH_2 = CH-COOH$, which polymerised in the presence of an initiator and accelerator to form polyacrylate chains:



The second grout belonged to the class of acrylate gels based on methacrylic acid, $CH_2 = C(CH_3)-COOH$. It had a similar polymerisation mechanism but a higher molecular weight of the polymer chains and a different component ratio. These differences affected its viscosity, gelation time, and adhesion to mineral surfaces. Both grouts were solvent-free and cured directly within a water-saturated environment.

The chemical resistance of these materials to alkaline, magnesium-bearing groundwater is related to their interaction with Mg^{2+} and Ca^{2+} ions. The carboxyl groups of the polyacrylate matrix, $-COO^-$, form coordination bonds with divalent cations according to the following reaction:



This reaction forms insoluble metal-organic complexes that provide additional crosslinking of the polymer network and increase its mechanical strength. Thus, the Mg^{2+} ions present in the groundwater of the serpentinite aquifer do not

degrade the grout as they do Portland cement. Instead, they act as an additional crosslinking agent that strengthens the polymer structure of the gel. The low viscosity of these grouts allows them to penetrate microcracks less than 0.05 mm wide, which is not possible with cement suspensions containing particles 15-40 μm in size.

Laboratory tests were conducted to compare the adhesion properties of two polyacrylate grouts under conditions representative of the aquifer at the DNK Mine. Rock samples with a mineralogical composition similar to that of the serpentinites in water-bearing sublayer IV-4 were prepared for testing. The samples contained at least 80% serpentine minerals, with inclusions of talc and magnetite. They were crushed to a particle size of 0.5-3.0 mm, corresponding to the typical particle-size distribution of disintegrated serpentinites within sublayer IV-4. Due to active serpentinisation and water saturation, these rocks partially transform into a loose, sandy material with a disturbed structure. Before mixing with the grouts, the prepared rock particles were wetted to reproduce aquifer conditions, with a degree of water saturation of at least 95%. To simulate the alkaline groundwater environment, the particles were kept in a magnesium hydroxide solution, $\text{Mg}(\text{OH})_2$, with a pH of 10.

The tests were conducted in two stages. During the first stage, the rock particles were mixed with each of the two polyacrylate grouts and examined under an optical microscope after 15, 30, and 60 min, as well as after 2 and 5 h. The microscopic examination focused on the coating of mineral particles by the polymer matrix, the uniformity of intergranular void filling, and the polymerisation behaviour of the grout in an alkaline, water-saturated environment.

During the second stage, each mixture of rock particles and grout was placed in cylindrical moulds with a diameter of 50 mm and a height of 100 mm. The specimens were then kept in a moist environment at a temperature of $20 \pm 2^\circ\text{C}$. The appearance and labelling of the consolidated specimens prepared for testing are shown in Figure 2.

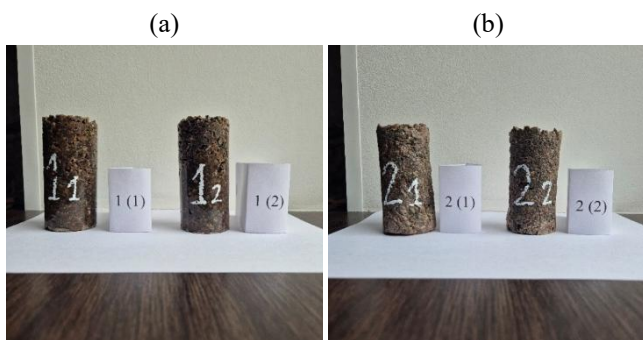


Figure 2. Consolidated serpentinite specimens prepared using two polyacrylate grouts before uniaxial compression testing: (a) grout 1; (b) grout 2

The specimens were labelled according to the grout type and curing period. For grout 1, specimens 1(1) and 1(2) were tested after 1 and 3 days, respectively. For grout 2, specimens 2(1) and 2(2) were tested after the same curing periods. The compressive strength of the consolidated specimens was determined by uniaxial compression testing using a GCTS ULT-200 hydraulic press. The rock mass strengthening factor was calculated as follows:

$$K_{str} = \frac{\sigma_c}{\sigma_{c1}}, \quad (10)$$

where:

σ_c – compressive strength of the consolidated specimen, MPa;

σ_{c1} – compressive strength of the unconsolidated rock, MPa.

The reference strength of the unconsolidated, disintegrated serpentinite was taken as $\sigma_{c1} = 2.28$ MPa. This value corresponds to the strength of the fragmented serpentinites in layer II and represents the limiting weakened state of the water-saturated rocks in sublayer IV-4 after a complete loss of structural integrity under aquifer conditions.

This factor links the laboratory test results with the geomechanical calculations and provides a quantitative measure of the increase in rock mass load-bearing capacity after grout injection. The K_{str} value was also used as an input parameter in the numerical model to assign the improved strength properties of the consolidated rock mass in Rocscience RS3.

The effectiveness of the proposed aquifer stabilisation technology was verified using finite element modelling in Rocscience RS3. The numerical model covered the depth interval of 1037.3-1062.3 m and consisted of 87216 finite elements, with mesh refinement near the shaft boundary. The model configuration and finite element mesh are shown in Figure 3.

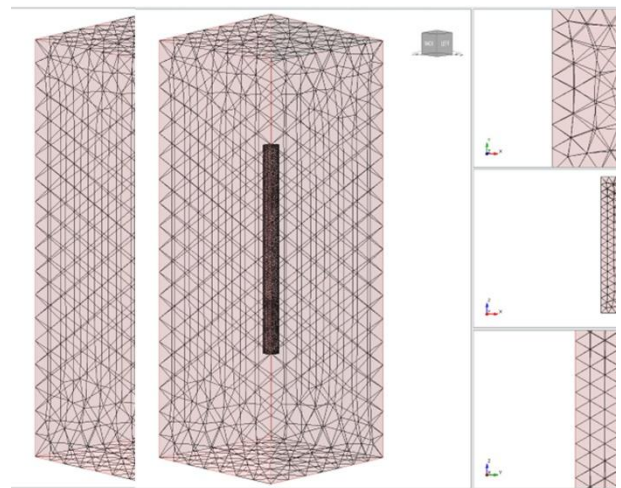


Figure 3. Numerical model configuration and finite element mesh in RS3

The clear internal diameter of the shaft was $D = 8.0$ m. Two cases were modelled: a shaft without advance rock mass grouting and a shaft surrounded by a 0.75 m thick rock zone consolidated with polyacrylate grout. The boundary conditions were specified according to the depth of the aquifer, $H = 1040$ -1057 m. The vertical stress was taken as $\sigma_v = \gamma H$ 27.2 MPa, while the horizontal stress was calculated as $\sigma_h = \lambda \sigma_v$, where λ is the lateral pressure coefficient determined from geomechanical calculations for the studied interval.

The parameters of the unconsolidated, water-saturated rock mass in sublayer IV-4 were specified considering the reduction in strength caused by water saturation and the geochemical aggressiveness factor $K_{gc} = 0.118$: $\sigma_c = 19.6$ MPa, $\varphi = 18^\circ$, $C = 1.15$ MPa, $E = 10.0$ GPa, and $\nu = 0.31$. The parameters of the consolidated rock mass were determined from the laboratory test results using a strengthening factor of $K_{str} = 2.28$: $\sigma_c = 6.1$ MPa, $E = 10.0$ GPa, and $\nu = 0.31$. For the consolidated rock mass, the internal friction angle and cohe-

sion were taken to be equal to those of dry serpentinite: $\varphi = 35^\circ$ and $C = 5.0$ MPa.

The strength factor (SF), defined as the ratio of rock strength to the stress acting at a given point in the rock mass, was used as the main stability criterion in the numerical model. At $SF \geq 1.0$, the rock mass is considered stable, whereas $SF < 1.0$ indicates that the rock is at or beyond failure and that failure zones may develop. The effectiveness of grouting was evaluated by comparing the SF distributions obtained for the two modelled cases.

3. Results and discussion

Microscopic examination of the interaction between the two polyacrylate grouts and serpentinite particles with a size of 0.5-3.0 mm in an alkaline, water-saturated environment ($pH = 10$) revealed clear differences in polymerisation behaviour and adhesion to mineral surfaces. Micrographs of grout 1 at different stages of polymerisation are presented in Figure 4, while those of grout 2 are shown in Figure 5.

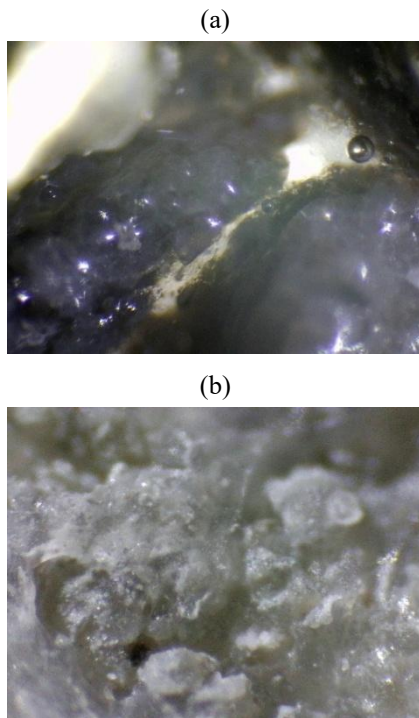


Figure 4. Micrographs of polyacrylate grout 1 with serpentinite particles at $pH = 10$: (a) initial stage of polymerisation after 30 min; (b) completed polymerisation after 5 h

Microscopic analysis of grout 1 showed that within 15-30 min after mixing, the mineral particles were actively coated by the polymer matrix, forming a continuous film on the surfaces of serpentine and magnetite grains. The rapid gelation of grout 1 in an alkaline, magnesium-bearing environment may be associated with the coordination binding of polyacrylate carboxyl groups with Mg^{2+} and Ca^{2+} ions according to Eq. (9). In addition, at $pH = 9-11$, acrylate groups may undergo ionisation under the action of hydroxide ions:

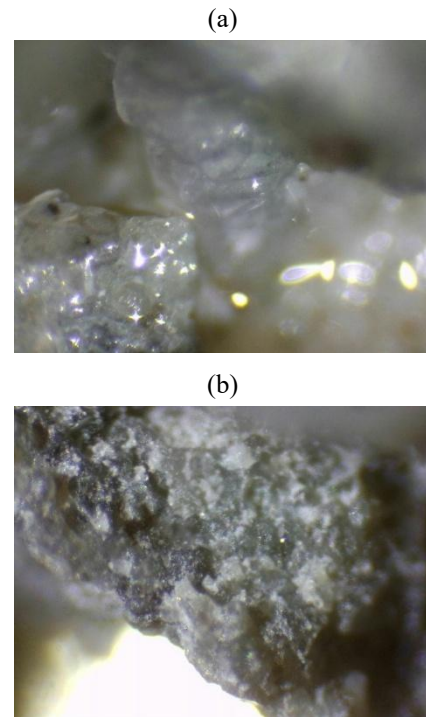
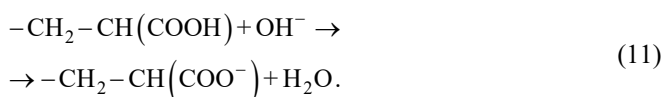
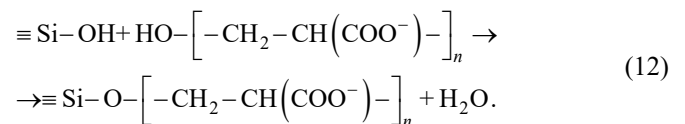


Figure 5. Micrographs of polyacrylate grout 2 with serpentinite particles at $pH = 10$: (a) initial stage of polymerisation after 30 min; (b) completed polymerisation after 5 h

The ionisation reaction in Eq. (11) increases the number of active carboxylate groups, $-COO^-$, that can form coordination bonds with Mg^{2+} ions according to Eq. (9). Thus, the alkaline environment of groundwater in serpentinite rocks does not inhibit the polymerisation of grout 1 and may increase the crosslinking density of the polymer matrix. Polymer-mineral bonding may also be promoted by the interaction between polyacrylate hydroxyl groups and the silicate surfaces of serpentinite minerals:

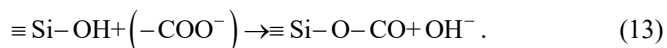


The interaction shown in Eq. (12) may promote bonding between the polymer matrix and the silicate surfaces of serpentinite minerals. This explains the high uniformity and density of the polymer network observed in the micrographs in Figure 4. The characteristic shiny inclusions correspond to serpentine minerals beneath the polymer coating, while the dark spots represent magnetite inclusions.

After 60 min, the polymer matrix of grout 1 uniformly filled the intergranular voids and formed continuous bridges between the rock particles. Polymerisation was completed within 2-5 h, and the intergranular space was completely filled with a homogeneous gel. This behaviour corresponds to the typical polymerisation kinetics of acrylate systems in an alkaline environment.

Grout 2 behaved quite differently. During the early stages of polymerisation (15-30 min), its polymer matrix was lighter in colour and had a clearly viscous consistency, but the coating of mineral particles was less uniform. This was particularly evident on talc surfaces. Talc, $Mg_3Si_4O_{10}(OH)_2$, has a layered structure with saturated siloxane bonds, $Si-O-Si$, on its basal surfaces. These surfaces are chemically inert and

provide no active sites for the adhesion of polymer molecules. One possible interaction mechanism on the edge surfaces of talc involves Si–OH and Mg–OH groups:



However, the number of these active sites on talc particles is considerably lower than on serpentine minerals. Consequently, grout 2 did not form a continuous adhesive film in areas containing talc inclusions. This is confirmed by the

micrographs in Figure 5, where breaks in the polymer matrix and unfilled pores can be seen in the dark areas containing talc. This difference in the adhesion of the two grouts to talc surfaces explains the difference subsequently observed in the strength of the consolidated specimens.

The results of uniaxial compression tests conducted on the consolidated cylindrical specimens using a GCTS ULT-200 hydraulic press are presented in Table 2. The specimens after testing are shown in Figures 6 and 7.

Table 2. Results of uniaxial compression tests on the consolidated specimens

Specimen	Grout	Curing time, days	σ_c , MPa	Height after testing, mm	Axial shortening, %	Deformation behaviour
1(1)	Grout 1	1	6.1	85.0	15.0	Plastic deformation without failure
1(2)	Grout 1	3	0.8	97.0	3.0	Plastic deformation without failure
2(1)	Grout 2	1	0.1	44.9	55.1	Brittle deformation with complete failure
2(2)	Grout 2	3	0.1	90.1	10.0	Brittle deformation with partial failure

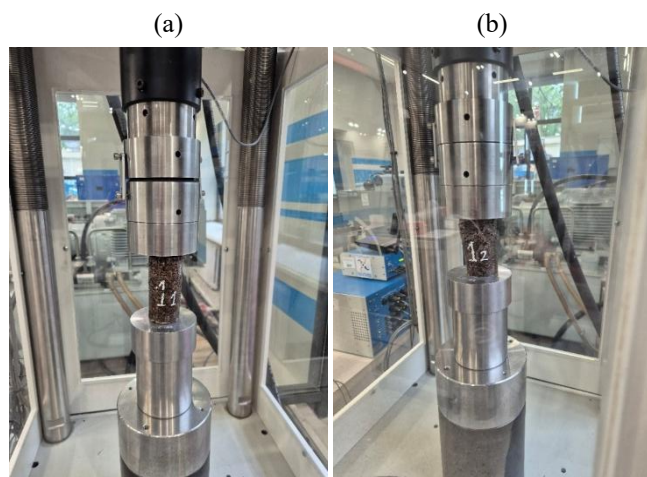


Figure 6. Specimens prepared with polyacrylate grout 1 after uniaxial compression testing: (a) specimen 1(1) after 1 day of curing; (b) specimen 1(2) after 3 days of curing

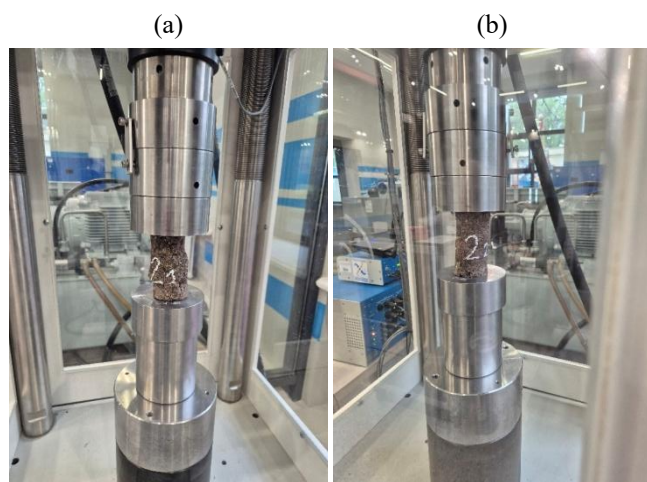


Figure 7. Specimens prepared with polyacrylate grout 2 after uniaxial compression testing: (a) specimen 2(1) after 1 day of curing; (b) specimen 2(2) after 3 days of curing

The results revealed clear differences in the strength and deformation behaviour of the specimens prepared with the two grouts. The specimens prepared with grout 1 showed considerably higher strength. The maximum compressive strength of $\sigma_c = 6.1$ MPa was recorded for specimen 1(1) after 1 day of curing, which was 61 times higher than that obtained with grout 2 ($\sigma_c = 0.1$ MPa). The variation in the strength of both grouts with curing time is shown in Figure 8.

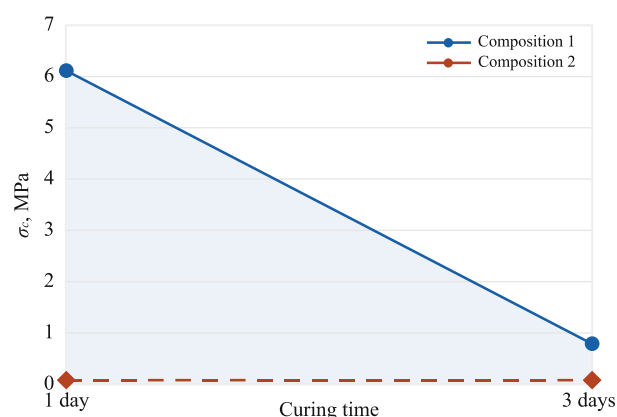


Figure 8. Compressive strength σ_c of the consolidated specimens as a function of curing time

The specimens prepared with grout 1 exhibited plastic deformation. Instead of brittle failure, they underwent uniform axial shortening while maintaining their integrity, as shown in Figure 9. The axial shortening of specimen 1(2) after 3 days of curing was only 3%, whereas that of specimen 2(1) reached 55.1%. This behaviour is particularly important under the conditions of a shaft aquifer, where the consolidated rock mass is subjected to long-term quasi-static loading caused by rock and hydrostatic pressures. The plastic behaviour of grout 1 is related to the highly elastic nature of the polyacrylate gel crosslinked by magnesium–carboxylate coordination complexes, $(-\text{COO})_2\text{Mg}$, according to Eq. (9). This polymer network can redistribute loads between its chains without brittle rupture.

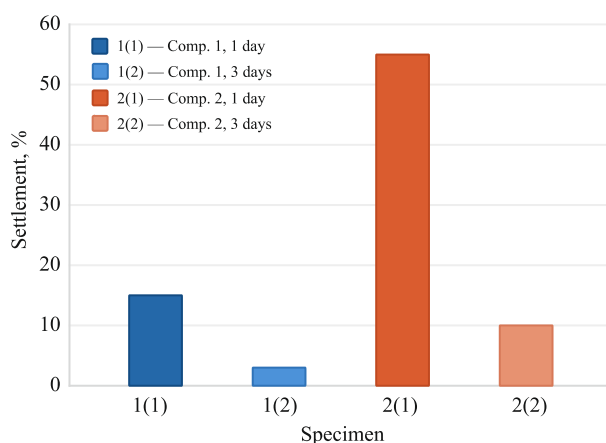


Figure 9. Axial shortening of the consolidated specimens after uniaxial compression testing

The specimens prepared with grout 2 showed considerably lower strength, with $\sigma_c = 0.1$ MPa after both curing periods. Specimen 2(1) lost its shape and underwent an axial shortening of 55.1%, indicating weak bonding between the polymer matrix and mineral particles. The absence of any strength increase between 1 and 3 days suggests that the interaction of grout 2 with the surfaces of serpentine and talc particles either ended at an early stage with the formation of a weakly bonded structure or failed to produce stable bonds. This finding is consistent with the microscopic observations.

For specimen 1(2) prepared with grout 1, the compressive strength after 3 days of curing was $\sigma_c = 0.8$ MPa, which was lower than that of specimen 1(1) after 1 day. This difference may be attributed to the variability typical of manually moulded specimens prepared from particulate materials, which may reach 30-50% of the mean value. Nevertheless, both specimens prepared with grout 1 retained their shape and integrity after testing, qualitatively confirming its greater effectiveness compared with grout 2. To establish statistically reliable relationships between strength and curing time, further studies should include 3-5 specimens for each curing period.

The rock mass strengthening factor K_{str} was calculated from the test results using Eq. (10). At the reference strength of the unconsolidated serpentinite, $\sigma_{c1} = 2.28$ MPa, the maximum strengthening factor obtained for grout 1 was 2.68. Thus, grout 1 increased the strength of the disintegrated serpentinite within the aquifer by a factor of 2.68. After grouting, the rock mass strength in sublayer IV-4 increased from 2.28 to 6.1 MPa, resulting in the formation of a stable water-sealing grouted zone around the shaft. This strength, combined with the monolithic concrete lining, is expected to improve rock mass stability and support safe shaft sinking through the aquifer while limiting groundwater inflow.

Thus, the combined results of microscopic observations and mechanical tests clearly indicate that polyacrylate grout 1 is preferable for use in the water-bearing sublayer IV-4 of the DNK Mine. Its advantages are associated with three interrelated factors. First, it remains chemically stable in an alkaline, magnesium-bearing environment: Mg^{2+} ions do not degrade the grout but strengthen its polymer network through $(-COO)_2Mg$ coordination crosslinks. Second, the consolidated rock mass reaches a high compressive strength of $\sigma_c = 6.1$ MPa and exhibits plastic deformation without brittle failure. Third, the grout provides a more uniform coating of both serpentine and talc mineral surfaces, as confirmed by microscopic observations.

Based on the laboratory results, an advance grouting scheme for stabilising the aquifer from the shaft bottom was developed, as shown in Figure 10. The grout is injected through boreholes with a length of $L = 25.0$ m, drilled at an angle of $\alpha = 5^\circ$ to the shaft axis and spaced 1.2 m apart. This creates a 750 mm thick annular grouted zone around the shaft. The boreholes begin 2.7 m above the roof of the aquifer, at a depth of 1037.3 m, and extend 5.3 m below its floor to a depth of 1062.3 m, providing complete isolation of the 1040-1057 m interval.

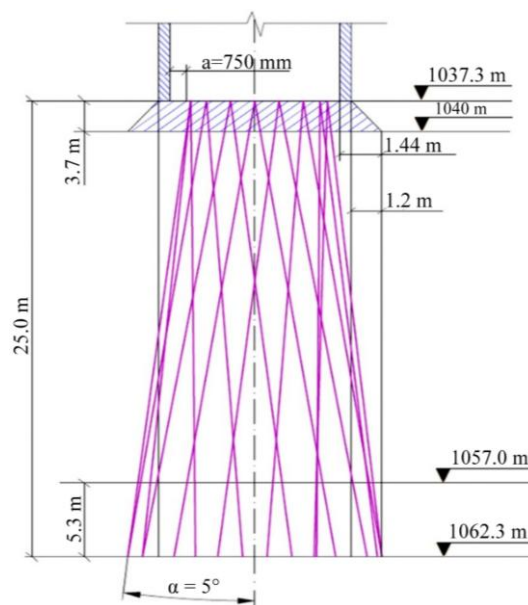


Figure 10. Advance grouting scheme for water-bearing sublayer IV-4 from the bottom of the Skipovoy shaft

To compare rock mass stability with and without advance grouting, the SF distribution was analysed in a horizontal section at a depth of 1037 m (Fig. 11) and in a vertical section along the shaft axis (Fig. 12). This made it possible to assess changes in the shape and extent of the zones with $SF < 1.0$.

A three-dimensional visualisation of the strength factor distribution near the shaft boundary is presented in Figure 13.

The numerical modelling results revealed clear differences in the stress-strain state of the rock mass between the two cases. In case 1, without advance grouting, the strength factor along the shaft boundary within the aquifer interval was $SF \approx 0.5-0.7$. These values indicate that the rock mass approaches failure and does not have the strength required for safe shaft sinking. In the horizontal section (Fig. 11a), an extensive zone with $SF < 1.0$ developed around the shaft and extended a considerable distance from its boundary. This indicates the formation of continuous potential failure zones and a high risk of groundwater inflow when the aquifer is exposed. The vertical section (Fig. 12a) confirms that the low-SF zone extends uniformly throughout the 1037-1062 m interval, with no local areas providing an adequate strength reserve.

In case 2, with polyacrylate grouting, the stress-strain state changed considerably. The minimum SF along the shaft boundary increased from 0.50 to 0.67, while the maximum value increased from 2.85 to 3.83. More importantly, the horizontal section (Fig. 11b) shows a concentric zone with $SF > 1.0$ around the shaft boundary. This zone forms a continuous ring of consolidated rock that acts as a water-sealing barrier.

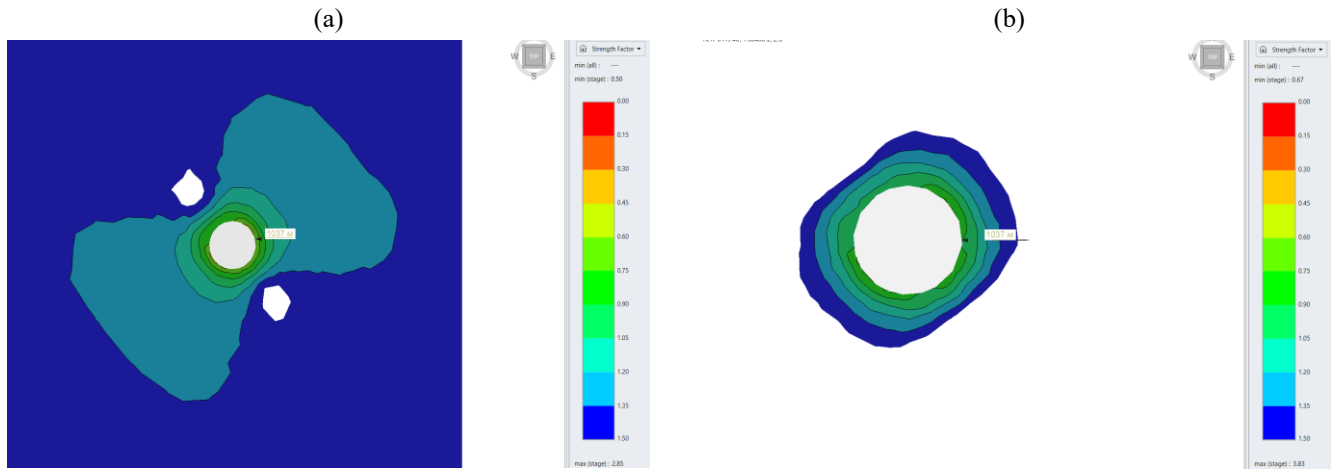


Figure 11. Strength factor (SF) distribution in a horizontal section at a depth of 1037 m: (a) without advance grouting, case 1; (b) with polyacrylate grouting, case 2

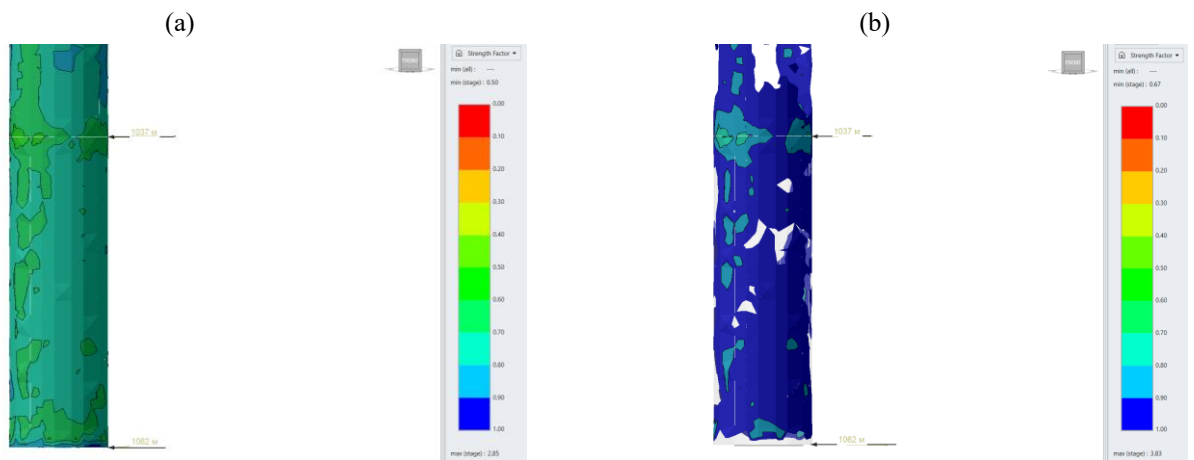


Figure 12. Strength factor (SF) distribution in a vertical section along the shaft axis within the depth interval of 1037-1062 m: (a) without advance grouting, case 1; (b) with polyacrylate grouting, case 2

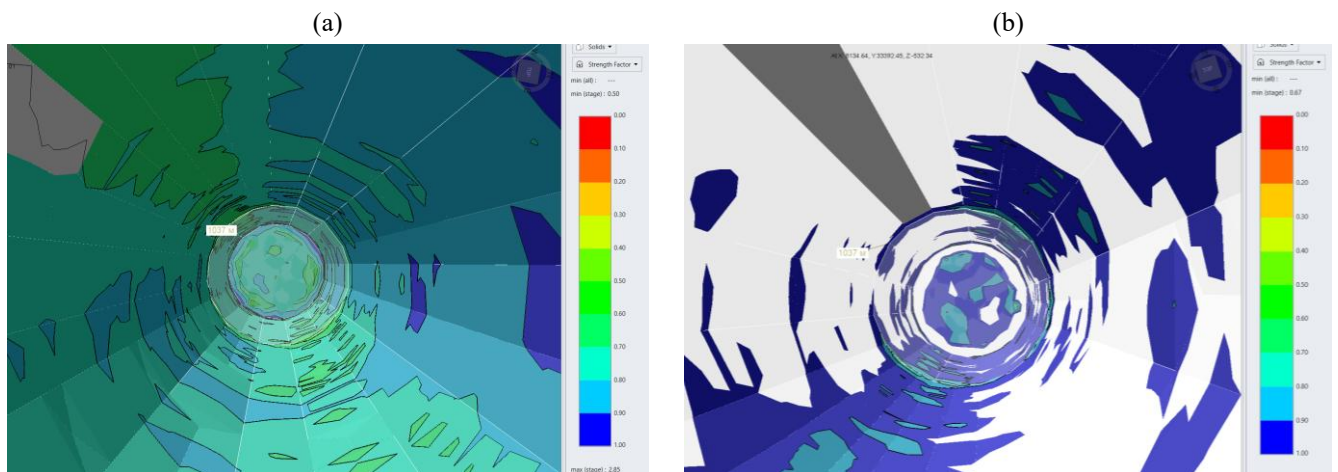


Figure 13. Three-dimensional visualisation of the strength factor (SF) distribution near the shaft boundary at a depth of 1037 m: (a) without advance grouting, case 1; (b) with polyacrylate grouting, case 2

The change from the green-cyan range ($SF = 0.5-0.9$) in case 1 to dark blue ($SF > 1.0$) in case 2 demonstrates the effect of grouting. In the vertical section (Fig. 12b), the consolidated zone extends continuously throughout the 1037-1062 m interval and beyond both the roof and floor of the aquifer, reducing the risk of water inflow through untreated sections.

The three-dimensional visualisation of the strength factor distribution near the shaft boundary shows that case 1

(Fig. 13a) contains extensive zones with $SF < 1.0$ directly adjacent to the shaft. These zones represent rock at or beyond failure and could lead to local rock collapse and uncontrolled groundwater inflow during shaft sinking. In case 2 (Fig. 13b), the same areas are shown in dark blue, corresponding to $SF > 1.0$. The rock zone consolidated with polyacrylate gel covers the potential failure areas and provides a stable shaft boundary around its entire perimeter.

The maximum principal stress σ_1 near the shaft boundary remained at a comparable level of approximately 24-47 MPa in both cases. This range corresponds to the natural stress field at the studied depth and indicates that grouting does not significantly redistribute the stress field. Instead, it increases the load-bearing capacity of the rock mass by improving its strength properties in accordance with $K_{str} = 2.68$.

Thus, the numerical modelling results indicate that advance grouting of water-bearing sublayer IV-4 with polyacrylate grout can effectively improve rock mass stability during shaft sinking at depths of 1040-1057 m. The laboratory results ($K_{str} = 2.68$; $\sigma_c = 6.1$ MPa), together with the increase in SF predicted by the numerical model, support the use of the proposed technology as an alternative to conventional cement grouting in alkaline, magnesium-bearing groundwater.

4. Conclusions

The geochemical conditions of water-bearing sublayer IV-4 at depths of 1040-1057 m in the 10th Anniversary of Kazakhstan's Independence Mine limit the effective use of Portland cement as a grouting material. The groundwater is alkaline (pH = 9-11) and contains high concentrations of Mg^{2+} and HCO_3^- ions and dissolved SiO_2 . In this environment, Portland cement undergoes magnesium-induced corrosion, producing loose brucite, $Mg(OH)_2$, and gradually losing its waterproofing properties. The geochemical aggressiveness factor $K_{gc} = 0.118$ indicates an approximately 8.5-fold reduction in the strength characteristics of water-saturated serpentinite, accompanied by a decrease in the internal friction angle from 35° to 18° and in cohesion from 5.0 to 1.15 MPa.

Polyacrylate grout 1, based on acrylic acid, provided stronger adhesion to serpentinite surfaces than grout 2, which was based on methacrylic acid. Microscopic observations indicate the possible formation of $(-COO)_2Mg$ coordination complexes between the carboxyl groups of grout 1 and Mg^{2+} ions in an alkaline environment at pH = 10. This interaction improves the chemical resistance of the grout and provides additional crosslinking of its polymer network. The weaker adhesion of grout 2 to talc surfaces, $Mg_3Si_4O_{10}(OH)_2$, is associated with the chemical inertness of Si–O–Si siloxane bonds on the basal surfaces of talc.

After 1 day of curing, the compressive strength of consolidated serpentinite specimens with a particle size of 0.5-3.0 mm prepared using grout 1 reached $\sigma_c = 6.1$ MPa. The specimens exhibited plastic deformation without brittle failure, with an axial shortening of 15%. Their strength was 61 times higher than that of the specimens prepared using grout 2 ($\sigma_c = 0.1$ MPa; axial shortening of 55.1%). The strengthening factor of the disintegrated serpentinite treated with grout 1 was $K_{str} = 2.68$, corresponding to an increase in strength from 2.28 to 6.1 MPa and supporting the formation of a stable water-sealing grouted zone around the shaft.

Finite element modelling in Rocscience RS3 using a model consisting of 87216 elements showed that, without advance grouting, the strength factor along the shaft boundary within the aquifer was SF = 0.50-0.70, indicating that the rock mass was close to failure. With polyacrylate grouting, the minimum SF increased from 0.50 to 0.67, while the maximum increased from 2.85 to 3.83. A concentric 0.75 m thick zone with improved stability formed around the shaft boundary and was designed to act as a water-sealing barrier.

The results demonstrate the potential of polyacrylate grouts for stabilising aquifers during vertical shaft sinking in serpentinite rock masses containing alkaline, magnesium-bearing groundwater. The proposed technology can be considered an alternative to conventional cement grouting under similar mining-geological and hydrogeological conditions. Further research should focus on optimising injection pressure, grout consumption per metre of borehole, and injection borehole layout to reduce costs while maintaining the required shaft stability.

Author contributions

Conceptualization: BB; Data curation: BB; Investigation: DA; Methodology: AA; Resources: YA; Software: AA; Validation: DA; Visualization: AA; Writing – original draft: BB, DA; Writing – review & editing: AA, YA. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Розроблення та обґрунтування конструкцій кріплення вертикального шахтного ствола у складних гірничо-геологічних і гідрогеологічних умовах

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Мета. Розроблення та обґрунтування технології ін'єкційного закріплення водоносного горизонту під час проходження вертикального шахтного ствола в серпентинітовому масиві з лужними магнієвмісними підземними водами, що обмежують ефективність традиційної цементації.

Методика. Дослідження включало аналіз геохімічних умов водоносного горизонту пласта IV-4 шахти "Десятиріччя Незалежності Казахстан" з визначенням коефіцієнта геохімічної агресивності середовища K_{gc} ; лабораторні випробування двох двокомпонентних поліакрилатних складів на консолідованих зразках серпентиніту фракції 0.5-3.0 мм у водонасиченому лужному середовищі при $pH = 10$; мікроскопічний аналіз процесу полімеризації; випробування на одноосовий стиск на пресі GCTS ULT-200; скінченно-елементне моделювання в Rocscience RS3 для масиву до та після ін'єкційного закріплення.

Результати. Встановлено, що геохімічні умови водоносного горизонту з $pH = 9-11$ і наявністю іонів Mg^{2+} , HCO_3^- та розчиненого SiO_2 обмежують застосування портландцементу внаслідок розвитку магнєзійної корозії. Коефіцієнт $K_{gc} = 0.118$ характеризує зниження несучої здатності серпентинітового масиву під час зволоження у 8.5 рази. Міцність зразків із першим поліакрилатним складом досягла 6.1 МПа при $K_{str} = 2.68$, що у 61 раз перевищує міцність зразків із другим складом. Чисельне моделювання показало збільшення мінімального значення SF із 0.50 до 0.67, а максимального – із 2.85 до 3.83 із формуванням навколо ствола зони підвищеної стійкості.

Наукова новизна. Обґрунтовано спільне використання коефіцієнтів K_{gc} і K_{str} для оцінювання геохімічного впливу та ефективності зміцнення серпентинітового масиву. Запропоновано інтерпретацію взаємодії поліакрилатного гелю з іонами Mg^{2+} через утворення координаційних комплексів $(-COO)_2Mg$.

Практична значимість. Запропоновано технологічну схему ін'єкційного закріплення водоносного горизонту через свердловини завдовжки 25.0 м, пробурені під кутом 5° , із формуванням навколо ствола закріпленої породної зони завтовшки 0.75 м. Застосування поліакрилатного складу підвищує стійкість водонасиченого серпентинітового масиву, знижує ймовірність утворення шляхів водопритоку та створює безпечніші умови для проходження вертикального ствола. Запропонована технологія може застосовуватися під час будівництва шахтних стволів в аналогічних гірничо-геологічних і гідрогеологічних умовах.

Ключові слова: шахтний ствол; водоносний горизонт; серпентиніт; поліакрилатний гель; ін'єкційне закріплення; коефіцієнт зміцнення; чисельне моделювання

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