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Grouting large karst zones at Dobrugea Coal Field in Bulgaria

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The Dobrugea coal field in Bulgaria is one of the most complex mining areas in the world for the reason of large karst zones, thick and deep aquifers and large amount of inflows. The most complex Valanzhin horisont is in the interval from 650 to 1350 m and is represented by the thick zones of karst limestones and dolomites, with the cavity sizes up to 3 m and more.

Anticipated water inflows into the shaft from this horizont are more than 25,000 m^3/hr at seam pressure 12 MPa and underground water inflow $5*10^{-3}$ m/sec. World practice does not have examples of shaft sinking at such abundance of water inflows.

To solve the problem of water inflows Production Association "Spetstamponazhgeologia" worked out the project of hydrodynamic investigations, supplied instruments and rendered methodical assistance in carrying out the project. Then taking into account the obtained data it implemented experimental grouting in the most watered strata of Valanzhin horizont. During the experimental grouting STG had to determine the possibility of installing grouting curtain within the most appropriate, according to hydrodynamic characteristics, intervals for Valanzhin, apply grouting process schemes developed for these conditions and to perform quality control of grout and grouting process.

Quality of investigations and reliable research was a top priority task so as the effectiveness of technique and implementation of grouting under the forementioned complex conditions much depends on reliable and comprehensive hydrogeological information.

For that purpose a new scheme for hydrodinamic investigations was used and downhole packers DAU-1 and flowmeters DAU-3M were applied. The investigations were implemented in intervals within the process of drilling approximately in 50 m (fig. 1). Each interval was tested at several overfalls of pressure during pumping and injection of water.

If was for the first time at Dobrugea coal field that investigations were carried out at intervals without casing and comprehensive hydrogeological information was obtained: seam pressure of underground waters, permeability coefficient, karst voidage, location, quantity, spacing and size of karstic cavities and share of fractures and karts within the whole voidage of rocks (table 1).

Table 1

Interval, m	Permeability coefficient 10^{-12}, m^2	Seam pressure, MPa	Anticipated waterinflow, m^3/hr	Total voidage, m	Max karst sizes, m
689-733	0.0418	6.12	25	13.7	0.03
733-783	2.83	6.60	2370	6.3	1.2
789-833	4.52	7.12	3430	21.7	1.4
840-883	5.18	7.62	3700	26.1	0.55
884-933	6.38	8.13	6080	16.4	2.7
933-983	4.40	8.63	4420	8.4	0.55
983-1033	0.498	9.13	710	5.9	0.2
1033-1083	1.36	9.63	1470	12.2	0.2
1083-1133	2.95	10.13	2840	13.8	0.83
1133-1183	0.299	10.62	310	13.4	0.36
1183-1233	0.0817	11.12	70	12.7	0.07
1233-1283	0.0142	11.61	20	7.3	0.008
1283-1335	0.0102	12.05	15	2	0.005

The principal problem during sealing of large karst zones is associated with the simultaneous process of grouting large waterbearing channels and small fractures and cavities.

In comparatively small channels it should be continuous grout flow. Grouting in large karst zones should prevent not productive spreading of grout. That can be secured by regulation of grout spread along the injection pipeline and changing its structural-mechanical properties during the process of grouting using injection regime.

Theoretical and experimental studies carried out by "Spetstamponazhgeologia" indicated the fact that size and strength parameters of sealing curtain during grouting in karst zones depend not on maximum sizes of karstic channels but on their sizes in narrow parts, "overclutches".

Generally the value of excessive injection pressure providing the spreading of viscous and plastic grout for radius r from the hole can be defined from the following equation:

$$\Delta P_0 = 2\tau r / \delta, \qquad (1)$$

where ΔP_0 - excessive injection pressure caused by pressure loss during grout flow in channels; τ - grout dynamic shear stress; r - grout spread radius; δ - grout channel size.

For the purpose of simultaneous injection of grout into completely different in sizes waterbearing channels we have:

$$r_1 / \delta_{ekv} = r / \delta_{av}, \qquad (2)$$

where δ_{ekv} - overclutch value of karstic channels; δ_{av} - average fracture aperture; r_1 ; r - grout spread radii of karstic channels and fractures of medium sizes.

Thus, taking into account the existing at Valanzhin horisont relationship of waterbearing channels sizes

$$\delta_{ekv}/\delta_{av} \gg 1 \qquad (3)$$

follows that $r_1 \gg r$ and during grout injection the grout spreads mainly along the channels with large section area and very limited - in thin fractures.

The single radius of grout spread in large channels as well as in thin fractures is secured from a relationship

$$\tau_c/\delta_{ekv} = \tau_0/\delta_{av} \qquad (4)$$

or

$$\tau_c = \tau_0\, \delta_{ekv}/\delta_{av}\ , \qquad (5)$$

where τ_c - maximum shear stress.

Taking into account that $\delta_{ekv}/\delta_{av} \gg 1$, the relation $\tau_c \gg \tau_0$ should be ensured.

It follows from this that to seal different by sizes waterbearing channels of Valanzhin horisont the grout formulation consisting of minimum two phases with their own rheological and structural-mechanical properties should be used.

On the bases of the performed theoretical and experimental studies a specific technology was developed which makes it possible depending on technological parameters of injection, to provide structural injection regime for viscous-plastic grout flow preserving main flow or injection regime undisturbed and at which no structuring takes place.

Thus, single grout formulation is used for grouting. But at first it is used for waterbearing horisont with high strength properties and it fills large karsts and cavities and then - for grouting smaller fractures.

Due to the peculiarities of this technology the grout is injected into large and small waterpermeable fractures, sealing them reliably.

Special grout developed in Spetstamponazhgeologia for the conditions of Dobrugea coal field was used during grouting Valanzhin horisont. The main components of grout are clay - based grout with structure - forming reagents.

For experimental grouting most permeable water-abundant intervals 886-903 m and 903-923 m were chosen.

Total anticipated water inflow from them was 6080 m^3/hr, and vertical sizes of karsts were about 2.7 m.

The grout was prepared and injected by high capacity grouting plant according to grouting process schemes developed by "Spetstamponazhgeologia" with automatic record of main parameters on chart strip of monitoring station SKTS-2M.

The grouting was performed using packers DAU-1 for shaft sealing, which were installed at the roof of the grouting interval (fig. 2).

Water inflows from Valanzhin horizont were reduced by nearly 1000 times after grouting.

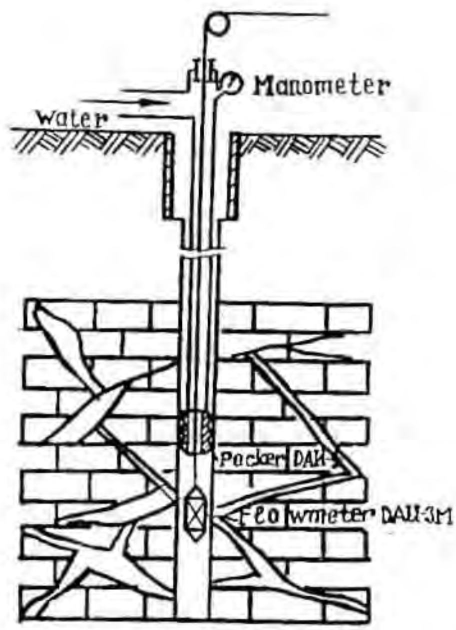

Figure 1. Technological scheme of hydrodynamic investigations at Valanzhin horisont.

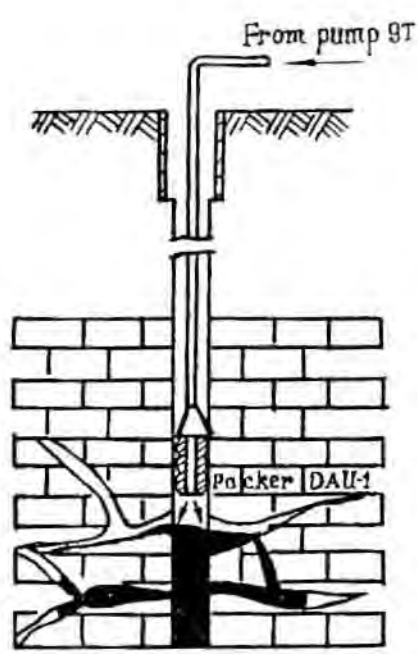

Figure 2. Shaft sealing scheme during grout injection.

Grouting of Karstified Aquifers During Shaft Drilling at Palazu-Mare Iron Ore Deposit

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ABSTRACT

The opening of the Palazu-Mare iron ore deposit located 2 km far from the Mamaya resort in Romania, had been designed by three vertical shaft bores from 650 to 1050 m deep. Shaft bores were planned to be drilled from 6.22 to 4.97 m in diameter within the interval of 50-500 m comprising intensively karstified water-bearing rock with predicted inflows to each future shaft of 185 m3/min to 200 m3/min. The problem consisted in the complexity of preventing lost circulations during shafting the karst zone and providing efficient cementation of casing in water-bearing strata.

Pregrouting programme designed and supervised by STG specialists was undertaken to ensure reliable sealing of karst zones in the shaft RA-1 drilling site. Grouting job was completed in two phases to cut down time period required for shafting. During the first phase rock treatment was performed through one hole drilled from the shaft sump and 3 holes drilled from ground surface in the interval of 50-260 m. During the second phase the interval of 260-500 m was treated through 3 holes drilled from surface with simultaneous shaft drilling up to a depth of 209 m.

As a result, the predicted shaft inflow in the interval of 50-209 m was decreased from 97.87 m^3/min to 0.015 m^3/min, or by 6000 times.

The paper deals with major parameters of grouting operations at shaft RA-1 of the Palazu-Mare deposit.

INTRODUCTION

The iron ore deposit of Palazu-Mare is located in the south-east part of Romania at the coast of the Black Sea between the towns of Constantsa and Ovidiu. The deposit was discovered in 1950 during prospecting of magnetic anomaly. Nowadays, the deposit has been prospected in detail and prepared for opening and exploitation.

The encountered rocks are represented by quartzites and amphibolites containing mostly magnetite. They occur as two irregular bodies in proterozoic cristalline rocks at depth of 500-1000 m.

The principal problem in the opening of the deposit is associated with shaft sinking in Jurassic carbonates that form a thick water-bearing layer of a karst-fractured type. Permeability values of the layer amount to 37.8 m/day.

The sinking of deep mine shafts under these severe conditions, both employing conventional drill-and-blast and shaft boring techniques, is a complex technical problem. This entails the development and implementation of a series of measures on installing the high capacity drainage system and employing the special types of shaft lining.

The Romanian specialists and scientists decided to open the deposit by vertical shaft bores taking into account the availability of relevant equipment, technology and great experience within field.

In connection with this, a decision was made to carry out pregrouting of the karst strata in the interval of 60-500 m to enable shafting in cavernous Jurassic carbonates. STG Agency prepared the project report and the grouting program was then supervised by the specialists from STG.

THEORETICAL PREREQUISITES TO DESIGNING SEALING CURTAIN PARAMETERS IN KARST ROCK

The calculations of sealing curtain parameters around a shaft in karst rock strata were performed according to methodology of STG. The prerequisite for efficient sealing of karst caverns is filling them with stabilized grout on account of providing the stabilized regime of grout flow in an injection pipeline.

The stabilized regime of grout flow is secured by sorting-out the pipeline diameter from a relationship:

$$d_{max} \le \frac{4\tau_0 H}{P_g - P_k} \tag{1}$$

where:
- τ_o - grout dynamic shear strength, MPa;
- H - vertical pipeline section length, m;
- P_g - hydrostatic head of grout column, MPa;
- P_k - groundwater head, MPa.

The optimum flow rate of grout is defined from an equation:

$$q = \frac{\pi d_{max} L}{4t} \tag{2}$$

where :
- t - time required for obtaining the specified value of grout strength, s;

Table 1. Principal parameters of the grout.

Parameters	Unit	Value
Density	kg/m^3	1340 + 1360
Static Shear Strength	Pa	86.5 + 92.0
Dynamic Shear Strength	Pa	135.8 + 166.0
Plastic Strength		
after 1 min	kPa	0.19 + 0.32
after 10 days	kPa	167.9 + 301.2
Allowable Plastic Strength	kPa	26.1
Structural Viscosity	Pa.s	(73.2 + 107.2).10 -3

DESIGN SOLUTIONS ON GROUTING

During design of the grouting program for the shaft RA-1 of the Palazu-Mare Deposit the following issues were solved:

- hydrogeological characteristics of the treated layers were defined;
- grout mix and injection process patterns were developed;
- grout curtain implacement parameters around RA-1 shaft were calculated (cover size in each zone, number of boreholes, grout injection volumes and regimes).

THE PROBLEM OF SHAFT BORING AT THE PALAZU-MARE DEPOSIT

Shaft boring in karstified and water-bearing rock strata has a number of problems. The principal ones are associated with lost circulations of mud and collapse shaft bore walls. Moreover, it is very difficult to provide a reliable cementation of casing due to inavitable losaes of cement grout.

The first phase for opening the Palazu-Mare deposit involved drilling of 3 vertical exploration shafts at the north-west (shafts RA-1 and RS-1) and at the south-east (shaft RA-2) flanks of the deposit with a designed depth of 650 m (RA-1) and 1050 m (RS-1 and RA-2), and also drifting of exploration workings.

The first shaft RA-1 designed for opening the deposit had initially a complex design (Fig. 1) according to which it was planned to install an intermediate casing column of 5160 mm dia. in the interval of 0-250 m. The casing was to overlap the most incompetent intensively karstified permeable zone of 110-210 m. Shaft drilling was carried out by shaft drilling rig type T-400 manufactured in Romania.

During the first half of 1986 the F-400 drilling rig was assembled over the RA-1 shaft site and the foreshaft with finished dia. of 6.4 m was drilled to a depth of 45 m. Then, a pilot borehole was drilled from the shaft sump within the shaft axis and up to a depth of 140 m employing the use of the f-400 rig. From a depth of 60 m the drilling of the pilot borehole proceeded under full lost circulation and was accompanied by rock cavings and stuck rods. During the course of drilling there were traversed karstic cavities 3+3.5 m thick at a depth of 110-115 m. At a depth of 140 m the drill string got stuck and further drilling of the pilot hole was stopped. The drilling program results showed that shaftsinking of the RA-1 shaft under such conditions would be impossible without preliminary specialist programs on sealing and strengthening the karst strata.

The grouting operations of the II phase were designed to be performed also through 3 inclined 500 m deep boreholes drilled from the ground surface.

GROUTING OPERATIONS

A special high-capacity grouting plant was designed and constructed at the shaft RA-1 comprising:

- automated storages fro clay powder and cement;
- centrifugal pumps for water;
- slurry pumps type 2PN-1200 for clay slurry;
- storage tanks for clay slurry;
- metal tanks.

Grouting operations of the I phase for implacing the grouting curtain in the zone of 60-260 m were performed through 4 boreholes. Hole No. 1 was drilled from the sump of the RA-1 shaft and boreholes 2+4 from the ground surface. The borehole No. 5 was employed for separate zones of the I phase.

Drilling of the borehole No. 1 was carried out by the Romanian drilling rig F-400. The boreholes 2+4 were drilled by the Soviet rigs 1BA-15H.

Prior to grout injection operations a progbram of geophysical logging and hydrodynemic testing was undertaken to define accurately the interval of karstic permeable zones and their hydraulic properties;

- caliper logging;
- inclinometer logging;
- electrical logging and radioactivity logging;
- acoustic logging;
- TV-acoustic logging;
- flowmetering logging applying packers;
- pressure build-up testing.

The program of investigations contributed to establishing the following:

- spacing, quantity, size and occurance of karstic caverns and large tissures;
- permeability of separate karstic zones;
- full and effective voidage of rocks;
- physico-mechanical properties;
- ground water chemistry.

Borehole investigations showed that the actual hydrogeologic conditions of the site were more complex in comparison with the results of geological prospecting that were used during the preparation of the project report.

The staff from STG supervising the grouting program introduced the necessary corrections into the program parameters.

The actual volumen and technological parameters of the I phase are presented in Table 3.

The overall volume of grout in the first phase program totalled to 29.905 m^3.

Quality control testing showed that a reliable circular sealing curtain was placed around the shaft in the interval of 60-260 m that will ensure shaft sinking and allow considerable simplification of the shaft design owing to the elimination of the intermediate 3160 mm dia. casing and sharply decrease the cost of shaft sinking.

Upon the completion of the I phase of grouting operations, the sinking shaft RA-1 was performed. Simultaneously, the grouting operations of the II phase were carried out. This involved drilling of boreholes No. 6 and No. 7 to a depth of 310 m and injection of 2520 m^3 of grout in the interval of 260-310 m. Nevertheless, all further activities on opening the Palazu-Mare deposit were terminated in 1990 due to changes occured in the investment policy of mining industry in Romania. By this time the shaft RA-1 has been successfully sunk to a depth of 209 m, the loss of drilling mud at this depth was only 0.015 m^3/min.

CONCLUSIONS

The grouting program for the RA-1 shaft of the Palazu-Mare deposit resulted in the following.

1. High efficiency the Intgegrated Grouting Technique in karstic environment has been proved.
2. Permeability of water-bearing rocks has been decreased on average by 6000 times in the interval of 60-260 m.
3. The sinking of shaft RA-1 up to a depth of 209 m has been successfully performed without any complications generated by lost circulation or collapse of borehole walls.
4. The Integrated Grouting Technique may be efficiently applied to resolve geotechnical problems during construction of the electric power station Ombla, Horvatija.

Table 2. Design Parameters of Grouting Curtain Formulation

Permeable Zones, m	M, m	K, $10^{-12}m^2$	R, m	r, m	m_t, 10^{-2}	V, m^3	N	V, m^3
60-110	50	18.5	15.0	14	2.6	800	3	2400
110-145	35	18.5	15.0	14	2.6	560	3	1680
145-148	3	-	26.9	15	100.0	2120	3	6360
148-160	12	18.5	15.0	14	2.6	195	3	585
160-210	50	8.0	15.0	14	2.0	615	3	1845
210-260	50	8.0	15.0	14	2.0	615	3	1845
260-310	50	43.8	15.0	14	3.4	1050	3	3150
310-360	50	3.6	15.0	14	1.6	495	3	1485
360-410	50	24.3	15.0	14	2.8	865	3	2595
410-460	50	13.4	15.0	14	2.4	740	3	2220
460-500	40	1.2	15.0	14	1.0	250	3	750
Total								24920

Symbol definition:

M - grouting zone thickness,
K - permeability,
R - grout curtain size around a shaft,
r - grout spread radius from a separate injection hole,
m_t- voidage,
V - grout injection volume in a separate hole,
N - number of grouting boreholes,
V - subtotal volume of grout.

Table 3. Phase I Volumes and Technological Parameters

Grouting Interval, m	Grouting Holes 1 V	1 P_i/P_r	2 V	2 P_i/P_r	3 V	3 P_i/P_r	4 V	4 P_i/P_r	5 V	5 P_i/P_r
60-77	936	55/15	304	70/45	278	80/15	365	70/50	-	-/-
77-110	1078	100/50	1132	65/30	1221	120/70	1296	110/60	-	-/-
114-145	1680	70/25	2112	120/30	1614	100/70	1748	120/70	-	-/-
145-165	510	100/60	643	100/70	635	100/40	480	100/70	370	40/15
165-210	185	80/50	2276	80/50	2398	70/40	2342	110/70	1091	70/40
210-260	-	-/-	1446	70/40	1765	100/55	1830	120/60	168	60/20

Symbol definition:

V - grout volume, m^3,
P_i - injection pressure, kg/cm^2,
P_r - residual injection pressure, kg/cm^2.

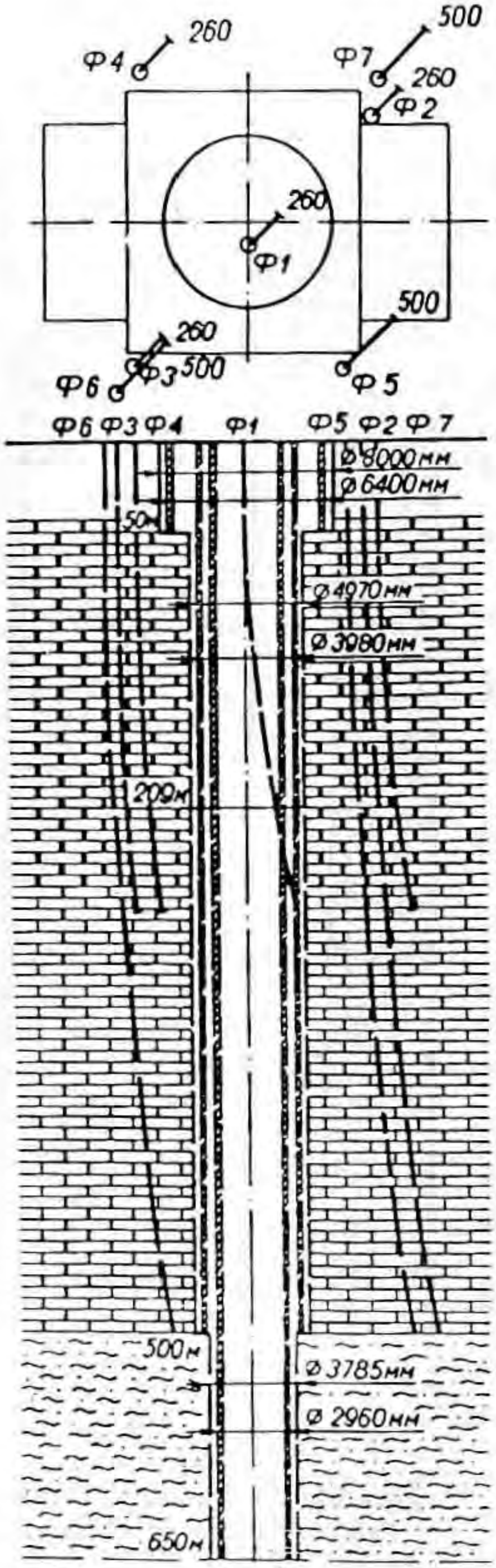

Figure 2. Schematic View of Grouting Holes Arrangement
Palazu-Mare Deposit, Romania