Consolidation of rocks in chamber workings and tunnels during the construction of underground hydroelectric power plants

U A Yatimov¹², A J Yatimov³, T A Yatimov³

¹Department of Town Planning, Engineering Systems and Networks, South Ural State University, 76, Lenin Ave., Chelyabinsk 454080, Russia
²Institute of Mineralogy of the South Ural Federal Research Center of MG of the Ural Branch of the Russian Academy of Science, ter. Ilmeny Res., Miass 456317, Russia
³Department of Underground Structures, Bases and Foundations, Tajik Technical University, 10 Ak. Radzhabovs St., Dushanbe 734042, Tajikistan

E-mail: umed1990@list.ru

Abstract. The article discusses the possibility of using reinforced cementation of rocks in order to consolidate the rock mass around underground workings and prevent water filtration into the turbine room and underground transformer room and tunnels of the Rogun HPP based on the experience of using this method in the construction of underground structures of the Kariba (Rhodesia) and Roselan-Bati HPPs (France). In recent years, comprehensive studies of rock masses containing the main underground structures of the Rogun HPP made it possible to clarify the current state of these masses and update the characteristics of their elastic and deformation strength properties obtained at the technical design stage. The results of the performed calculations testify to the normal operation of the anti-seepage circuit of the dam and indicate high efficiency of the drainage system of the pressure head unit.

1. Introduction

Before the development of technology for injecting cement slurries under high pressure and the creation of appropriate equipment, filling the space between the wall of rock and the tunnel lining was carried out only with the help of filling cementation at a pressure of 3-5 atm. The purpose of this grouting was to fill in the inevitable voids between the lining and the rock and obtain a tight abutment between the lining and the rock. This cementation does not ensure consolidation of the rock and reduces its water permeability. Therefore, the main bearing of the waterproof structure of the tunnels was the lining, which was calculated and designed accordingly. With the growth of heads and diameters, the linings became heavier, and the use of metal linings was required. Meanwhile, it is obvious that if fast-setting solutions are injected into the rock to a great depth under high pressure, then it is possible to create a zone of prestressed waterproof rock around the tunnel, which makes lining significantly easier.

In modern industrial practice, strengthening cementation of rock under significant pressure and to great depths is one of the most important works in the construction of high-pressure tunnels and mine turbine water pipelines in fractured and water-tight rocks. Such cementation is also used around
underground buildings of hydroelectric power plants, both for rock consolidation and in order to reduce infiltration [1-2].

The current trend is to bring the grouting pressure to a value equal to twice the maximum operating head in the tunnel. It is recommended to perform cementing in stages with increasing pressure as the wells deepen. However, the magnitude of the grouting pressure should not exceed the weight of the overlying rock column and correspond to the bearing capacity of the lining, calculated for external uneven pressure. On the other hand, the grouting pressure should not be less than the groundwater pressure [3-6].

2. Reinforced cementation of rocks around underground workings

An example of reinforced cementation around an underground building is the Kariba HPP (Rhodesia). The capacity of HPP Kariba on the Zambezi River in Rhodesia is 600 MW in six units. The head is created by an arched dam with a height of 128 m. During the construction of this hydroelectric power station, large cementation works were carried out (Figure 1) [7-8].

![Figure 1. Cross section of Kariba HPP:1 - water intakes No. 1,2,5 and 6; 2 - water intakes No. 3 and 4; 3 - temporary water intakes; 4 - shaft for lowering the sandoor; 5 - segment working gates; 6 - grooves for sliding shields; 7 - temporary position of segment gates; 8 - diaphragm with hydraulic resistance; 9 - water conduit with concrete lining; 10 - water pipelines with metal lining; 11 - chamber of suction pipe gates; 12 - surge tank; 13 - ventilation gallery; 14 - outlet tunnels; 15 - temporary approach tunnel; 16 - machine room; 17 - transformer room.](image)

The building of the hydroelectric power plant is located at a depth of 100 m from the NRL (normal retaining level) and 160 m from the earth's surface. The rocks in the intake zone are represented by fractured quartzites, lower in the area of the turbine hall - gneisses, in places strong, in places broken. The gneisses are cut in places by pegmatite dikes. In order to consolidate the rock mass around the underground workings and prevent water filtration into the powerhouse and underground transformer room, the rocks around them were cemented (Figure 2).

The main grout curtain was supplemented by grouting "umbrellas" made from under the vaults of the machine and transformer halls, as well as from the balance chamber, from the side of the water intake. An additional grouting curtain in quartzite from the side of the water intake was implemented in the first place and served as protection against water filtration from the filling water reservoir when performing concrete work in mines.
Figure 2. Geological conditions and grouting scheme at the Kariba HPP: 1 - fractured quartzites with interlayers of destroyed quartzites and clays; 2 - line of contact of quartzites with gneisses; 3 - strong gneisses; 4 - fractured and destroyed gneisses with an interlayer of ground rocks; 5 - strong gneisses with tectonic fractures; 6 - drilling zone for cementation; 7 - grout curtain in front of water intakes; 8 - grout curtain; 7 - enveloping water intakes and going inside the slope; 9 - the main grout curtain along the line of pressure water conduits and gate shafts; 10 - contours of underground structures.

In order to consolidate the rock that was weakened and destroyed by explosions, cementing was also carried out from equalizing chambers and shield shafts using radial horizontal wells 4.6 m deep, located at a height of 4.6 m and at a pressure of 3.5 atm. Thus, a continuous grout curtain was created between the shield shafts, located between the reservoir and the machine room. The "umbrellas" above the vaults were formed by a grid of radial wells with a depth of 4.6 m, cemented in three stages. First of all, the grout was injected at a pressure of 1.4 atm through the wells with a depth of 0.9 m, to fill voids between concrete and rock. In the second stage, the wells were deepened 3 m into the rock and permeated at a pressure of 3.5 atm. Finally, in the third stage, the rock was permeated to a depth of 4.6 m at a pressure of 10.5 atm. In those cases, when, in the second stage, the fluid was not permeated well into the rock, the pressure was brought to 10.5 atm. instead of 3.5 atm.

Cementation behind the walls of the turbine hall was also performed in three stages:
- the first - at a pressure of 1.4 atm. to a depth of 0.6 m;
- the second - at 3.5 atm. to a depth of 3 m through sealed wells to a depth of 0.6 m;
- the third - at 10.5 atm. to a depth of 8.5 m through plugged wells to a depth of 3 m.

The unlined sections of the rock were also cemented in three stages in a similar way, but in the first and second stages through conductor pipes embedded in the rock at 0.3 m. Cementation begins, as a rule, with the injection of grout consisting of 1 part of cement and 30 parts of water and then the amount of water was gradually reduced until the design pressure was built up. After that, a solution of the composition 1:6 was taken, which was used for cementation. In the presence of areas in which the pressure did not rise even at a composition of 1:1, then sand was added in an amount equal to the amount of cement.

The vault of the turbine hall was cemented, starting from the downstream side, with the wells of the first stages always ahead of the wells of the stages with high pressures. When more than 228 kg of cement was absorbed, the well was flushed out and cemented again. If the absorption of cement reached 910 kg, a new additional well was drilled in the interval between the planned ones through which the injection was carried out.
During 32 months of cementation work, 7003 wells with a total length of 40132 m were drilled with a maximum monthly productivity of 3725 running meters. The total consumption of cement amounted to 7612 tons and sand 1963 tons, with a maximum monthly consumption of 1370 tons of cement and 467 tons of sand.

The reliability of grouting is characterized in such a way that when the water level in the reservoir is 73 m above the top of the turbine room (its highest level will be higher by another 24 m), there are several small leaks in the vault, they give drops to the protective vault, but the total amount of infiltrated water is so small that it has time to completely evaporate. The vault of the transformer room is practically dry. The rocky surfaces of the walls are sometimes damp and even wet, but the amount of water flowing into the drainage system is so small that it can be neglected. Obviously, the cementation of rocks around the underground structures of the Kariba HPP has yielded positive results. Another example is the consolidation of fractured rocks when driving a pressure tunnel at the Roselan-Bati hydroelectric power station (France) [7].

In the middle part, the tunnel route crosses a vast zone of highly destroyed rocks with a length of 75 m along the route with pressurized groundwater. For the description of the penetration of this difficult section see Figure 3. In the first 25 m of this section, the tunnel passes through highly fragmented coal shale; in the next 50 m, crushed and ground quartzites and Triassic limestones were encountered. The head of groundwater here reached 14 atm. At the contact of these rocks and the solid crystalline schists that follow them, there was a small section of fractured crystalline schists, in which the head reached 19.5 atm.

Figure 3. Roselan Bati tunnel driving scheme: 1 - groundwater pressure 14 kg/cm²; 2 - groundwater pressure 19 kg/cm²; 3 - the first stage of consolidation to a depth of 45 m; 4 - the second stage of consolidation to a depth of 40 m; 5 - galleries of preliminary reconnaissance; 6 - exploration wells; 7 - crystalline shales; 8 - coal shale; 9 - crushed Triassic limestones; 10 - Triassic limestones and finely crushed quartz, ground.

Conventional drilling methods in weak water-saturated soils were not applicable for this case. Various special methods were used in the study. The very high pressure of groundwater and the presence of large blocks in the rock excluded the use of shield penetration. The use of freezing was technically and economically unacceptable. Drainage as a partial measure could probably significantly reduce the difficulty of driving, but it can be said in advance that these rocks are poorly drained. In order to test the drainage capacity of the rock, three wells with a diameter of 90 mm were drilled, but only one of them gave a very mediocre result (2 l/s). The other two got full very quickly. The groundwater pressure, despite the fact that their inflow into the tunnel through the crystalline shale
was up to 40 l/s, did not drop for several months. Based on all this, the drainage device was also abandoned in order to reduce the pressure of groundwater.

In the end, it was decided to apply the method of rock concentration by high pressure cementation, similar to how it was done at one of the sections of the Malgover HPP tunnel. However, it should be noted that conditions at the Malgover HPP were much easier, since the length of the section was less than 25 m and the groundwater pressure did not exceed 4.5 atm.

When driving a section of the Roselan-Bati tunnel, the following method was applied (Figure 4). A 10 m long working chamber with a reinforced concrete lining and a frontal wall was made in strong crystalline shales in front of the destroyed rocks. The rock behind the lining has been carefully injected with the grout. Further work was carried out in two stages.

First, a bundle of diverging wells was drilled through the frontal wall, forming concentric cones and having a slight inclination to the axis of the tunnel. Wells were drilled to a depth of 45 m in zones of 5 m in shale and 3-4 m in Triassic rocks with immediate injection of consolidating solutions. In total there have been 96 wells drilled with a total length of 3070 m.

First, solutions of sodium silicate and sodium bicarbonate were injected into each zone at a pressure of 70 atm. Then under pressure from 80 to 150 atm. grout was injected. Only for the coal shale the grout injection pressure was up to 70 atm.

The setting speed and strength of the hardened silicate solution depend on the ratio

$$\alpha = \frac{\text{bicarbonate weight}}{\text{silicate volume at 35° V}},$$

and the viscosity of the solution, which determines its ability to penetrate into the soil, depends on the ratio

$$\beta = \frac{\text{bicarbonate weight}}{\text{silicate volume at 35° V}}.$$

Preliminary experiments have established the optimal values of the ratios $\alpha = 0.153$ with a setting time of 30 min and $\beta = 4 - 8$.

Grout was prepared with a water-cement ratio of 2 on slag cement grade 250-315. The wells were drilled simultaneously by four Krelius rotary drilling rigs.

To make sure of the reliability of rock consolidation and formation of a consolidated zone with a thickness of at least 5 m around the future drilling, 10 control wells were drilled. After that, 8 additional wells with a total length of 686 m were drilled and re-injected with clay-cement mortars.
The clay-cement and water – cement ratios in this case varied from 0.3 to 0.75 from 1 to 2 respectively. Consolidation of the first section with a length of 46 m was completed in 3 months.

After the completion of the consolidation, excavation work began, which was carried out as follows. First, the upper guide stroke of the minimum section was passed. With a lag of several meters, the upper half of the tunnel section was expanded with the installation through 0.75 m of an arch support with a diameter of 5.25 m from I-beams No. 18 and longitudinal beams from paired corners 100x200. The space between the arches was concreted. A reinforced concrete front wall was built at the end of the guideway, which passed only 36 m, so that a fixed soil layer of about 9 m remained ahead of the face. Following the fastening of the upper part of the section, the expansion and fastening of the lower part was carried out with the installation of the lower support elements of the half-rings from the same I-beams and angles. Under the protection of this fastening, the main lining of the tunnel with an inner diameter of 4.4 m and a thickness of 0.4 m was carried out with double reinforcement with a diameter of 40 mm, installed after 45 cm. Table 1 shows the scope of consolidation work.

| Indicators                        | Unit of measure | Volumes |
|-----------------------------------|-----------------|---------|
| Fixed section length              | m               | 46      | 40      |
| Main drilling molding             | run.m           | 4068    | 2538    |
| Re-drilling molding               | run.m           | 10000   | 17 284  |
| Silicate consumption              | m³              | 370     | 414     |
| Silicate solution consumption     | m³              | 1765    | 2899    |
| Cement consumption                | t               | 692     | 1074    |
| Clay consumption                  | t               | 15      | 102     |
| Development area length           | m               | 37.7    | 40.0    |
| Rock mining volume                | m³              | 1000    | 1080    |
| Explosive consumption            | kg              | 243     | 100     |
| Metal consumption for fastening   | t               | 44      | 46      |

The development of coal shale was carried out partly with the help of small explosions, and consolidated quicksand - only with jackhammers. Based on the experience of consolidation of the first section, it was decided to go through the second section in one step using the same method with the following changes. It was decided to take the thickness of the consolidated soil in the upper half of the tunnel equal to 7 and in the lower half, 4 m. The number of wells was 72 with their placement in eight rows; the total length was 2161 m. The depth of the cementation zones was reduced to 2.5 m. The setting time of silicate solutions was reduced to 15 minutes, and the coefficients $\alpha$ and $\beta$ were taken, respectively, 0.16 and 6. Cement solutions were used only with the addition of clay for clay - cement ratio of 0.25. After injection, 19 control and 8 additional wells were drilled into the main wells to enhance the consolidation of the selected area.

The second section was consolidated in the same way as the first, with the only difference that the expansion of the lower half of the section was started only after the upper half expansion was completed and it was secured along the entire length, since the experience of working in the first section showed the inconvenience of working with a ledge.

Silicates play a significant role in creating water impermeability by filling voids in the rock with helium silicate. They also increase traction. A big advantage of silicates is the ability to pump them at a relatively low pressure compared to cement grout.

The effect of silification on cement mortar injection is of secondary importance. Siliconization prevents water from squeezing out too quickly. When cementing, the use of clay-cement mortars is
more effective. When injected under high pressure, penetrates into the weaker layers and compresses the rock.

The cement stone thus plays the role of more than just a waterproof element. It squeezes water out of already silicified rock masses, compacts it and increases adhesion, making the rock also waterproof and more durable. However, one should not consider the applied method of fixing weak rocks as universal for all similar cases. In each particular case, it is necessary to thoroughly study the local conditions and characteristics of the rocks: their grain size distribution, physical and mechanical properties, chemical composition, groundwater pressure, etc.

It should be noted that the cost of mining this section turned out to be 15 times higher, and the duration of the work - 30 times longer than when mining in a good rock. According to the project, the underground building of the turbine hall of the Rogun HPP is located in the strata of the left bank of the river. Vakhsh at a depth of about 400 m from the earth's surface. The turbine hall is 70 m high, 21 m wide and 220 m long. At a distance of about 60 m from the turbine hall towards the downstream, there is a transformer room, which has design dimensions of 19x36x200 m.

The bedrock in this area is represented by a stratum of Lower Cretaceous continental deposits of interbedded sandstones and siltstones (the Obigarm suite K1ob1). At the initial pickets, the turbine room chamber is located in the siltstone massif of the Lower Obigarm suite (K1ob1), the layers of which have a dip azimuth of 125-130° and are inclined towards the downstream at the angle of 65-75°. At the same time, siltstones compose ~30% of the massif along the length of the turbine hall. Further, along the entire length to the bottom, the host rocks of the turbine hall are thick-slab sandstones of the Higher Obigarm suite (K1ob2) [9-12].

The rock mass is complicated by the development of tectonic fractures of the V-VI orders, as well as the presence of two tectonic faults of the IV order (No. 70 and No. 273), with an azimuth of 345-350° and an angle of incidence of 30-50°.

The influence of tectonic disturbance No. 35, which passes below the turbine room chamber, can be expressed in the form of intense rock fracturing during further driving of the turbine hall up to the design marks (Figure 5) [13-14].

![Figure 5. Section along the axis of the Rogun hydroelectric power plant: 1 - repair flat gate; 2 - emergency repair flat shutter; 3 - knot of the upper knees; 4 - machine room; 5 - transformer room; 6 - repair flat gate.](image)

3. Discussion

At present, computational and comprehensive studies addressing options for additional fastening of chamber workings and tunnels of the Rogun HPP and ensuring and operational reliability are carried out by several organizations - JSC "Institute Hydropject", consulting firm "Coyn Bellier" (France) and the company "Tajikan "And TsSGNEO [15-18].

The construction of a geofiltration model of the rock mass located at the base of the rock-earth dam of the Rogun HPP and containing the underground workings of the head station unit is carried out on
the basis of the available information about the geological and hydrogeological structure, topographic survey data, the corresponding design and layout drawings containing information about the structure and materials of structures.

The mine workings have been integrated into the base solid model. Also, an anti-seepage grouting curtain of the Rogun HPP dam was integrated into the model [19-20].

Thus, the analysis of the calculation results testifies to the normal operation of the anti-seepage circuit of the dam and shows the high efficiency of the drainage system of the head station unit construction.

The complex studies of rock masses containing the main underground structures of the Rogun hydroelectric power station carried out by TsSGNE O in recent years made it possible to clarify the current state of these rock masses and update the characteristics of their elastic, deformation strength properties obtained at the stage of the technical design [21-22].

4. Conclusions

The obtained experiments allow us to conclude that for the consolidation of the rock masses around the turbine hall and the transformer room of the Rogun HPP under construction, it is possible to envisage large-scale works on the installation of grout curtains and grouting of the rock behind the lining of structures in order to prevent water filtration as much as possible, as well as drain the filtered groundwater in order to avoid their significant pressure on the lining of underground structures. However, one should not consider the applied method of fixing weak rocks as universal for all similar cases. In each particular case, it is necessary to thoroughly study the local conditions and characteristics of the rocks: their grain size distribution, physical and mechanical properties, chemical composition, groundwater pressure, etc.

For the safe conduction of work in the turbine hall at the stage of completion, as well as for the normal subsequent operation of technological equipment, it is necessary to ensure that a number of conditions are met. Thus, it is very important to minimize the negative impact of the forthcoming development of the turbine hall on the state of the enclosing rock masses, which has already undergone significant displacements, i.e., penetration should not be carried out with a continuous face, but only in aggregate with reinforcement with design concrete. When developing a rock, limit the maximum volume of explosive charges. During excavation, constant monitoring of the displacements of the array should be carried out. Consideration should also be given to the possibility of improving the strength properties of the enclosing rock masses by cementation, as well as strengthening its fastening by installing additional anchors and / or spacers.

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