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Adaptability and Construction Practice of High-Pressure Jet Grouting in Reservoir Seepage Control and Reinforcement

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Abstract: ***Most reservoir danger-elimination and reinforcement projects fundamentally involve seepage control and structural reinforcement of dam foundations, dam abutments, and dam bodies. Among the available seepage prevention technologies, high-pressure jet grouting has gained widespread application owing to its broad geological adaptability and proven effectiveness. This paper focuses on the adaptability of high-pressure jet grouting technology to diverse engineering geological conditions, as well as on the successful implementation of its construction methods, processes, and operational procedures as demonstrated in the Dama'an Reservoir project. The study first characterizes the geological conditions of the project site and identifies the seepage control requirements that govern the selection of grouting technology. It then examines the construction methods and operational procedures adopted in the Dama'an Reservoir project, including the selection of grouting parameters, the control of construction quality, and the treatment of adverse geological conditions. The implementation results are analyzed to assess the adaptability and effectiveness of the technology under the specific site conditions encountered. On this basis, the paper summarizes the key technical points and practical experience derived from the project, and discusses the conditions under which high-pressure jet grouting can be reliably applied in comparable settings. The findings aim to provide an effective technical reference for seepage prevention and reinforcement in similar water conservancy dam projects, and to support the rational selection and application of grouting technologies in reservoir reinforcement practice.***

Keywords: High-pressure jet grouting, Reservoir reinforcement, Seepage control, Dam foundation treatment.

1. INTRODUCTION

High-pressure jet grouting technology is an important method for dam seepage prevention, soft soil foundation seepage prevention and foundation reinforcement. It is widely used in the foundations of water conservancy dam projects, industrial and civil buildings, etc., and has significant effects in water conservancy project dam reinforcement and leakage treatment. High-pressure jet grouting technology has the characteristics of wide adaptability and reliable effect for soft soil foundations and dam seepage prevention. Through precise and specific construction parameter control and quality inspection, significant engineering seepage prevention effects can be achieved, thereby improving the safety and durability of dam projects, especially reservoir projects. Further enhance the comprehensive management capacity and information management capacity of water conservancy projects, and restore and improve the comprehensive utilization benefits of water conservancy projects. Therefore, through the application of actual engineering cases and continuous improvement of construction technology experience, this technology will play a more important role in future water conservancy projects.

2. OVERVIEW OF HIGH-PRESSURE JET GROUTING TECHNOLOGY

The main principle of high-pressure jet grouting technology is to use the action of high-pressure jet to agitate the stratum, and the injected grout is mixed and solidified with the soil to achieve the purpose of seepage prevention and reinforcement. The specific technical principles include cutting and mixing, lifting and replacement, filling and extrusion, and infiltration and coagulation.

2.1 Technical Principles and Characteristics

The basic principle of high-pressure jet grouting is to insert a grouting pipe with a special nozzle into the predetermined depth of the stratum through a drilling rig, use high-pressure (35-40 MPa) water jet to cut the soil, and simultaneously inject cement slurry and air to mix and solidify the slurry with soil particles, forming a continuous, high-strength anti-seepage curtain or wall. Technical advantages: simple equipment, mature technology. Relatively low cost. Reliable wall quality, high work efficiency, and good controllability. Good anti-seepage effect, the formed consolidated body has a low permeability coefficient (up to 10-6 cm2/s), and the

compressive strength reaches 2~12 MPa79. Flexible construction, no need for large-scale excavation, little disturbance to the dam body, low noise, and excellent environmental protection. Wide applicability. Disadvantages: Drilling deviation is prone to occur when the depth is large, and the lower part of the jet grouting wall is prone to branching. The anti-seepage performance is not as good as that of concrete anti-seepage walls.

2.2 Construction Methods and Applicable Conditions

High-pressure jet grouting technology has a variety of construction methods, including single-pipe method, double-pipe method, triple-pipe method and multi-pipe method. The specific principles and applicable conditions need to be reasonably selected according to engineering requirements and geological conditions.

For anti-seepage reinforcement of dam foundations in soft soil foundations, such as mucky soil, sand layers, and sandy gravel strata, a continuous anti-seepage wall is formed through jet grouting piles to reduce leakage risks.

For complex contact zones, such as the contact zone between clay core walls and weathered bedrock, grouting covers are formed through jet grouting to cut off fissure leakage.

For plugging dam cracks and leakage points, directional jetting is performed on internal cavities and cracks of the dam body, and cement slurry is filled to restore structural integrity.

For curtain grouting, a continuous anti-seepage curtain is set along the dam axis to lower the phreatic line and prevent piping and contact erosion.

2.3 Brief Description of Construction Process

Detailed geological exploration and scheme design are carried out before construction. High-pressure jet grouting construction is carried out according to design requirements. After construction, quality inspection and acceptance are carried out.

2.4 Key Construction Techniques

Drilling and positioning: Geological drills or impact drills are used for hole formation. The hole position deviation must be ≤ 5 cm , and the hole slope must be controlled within 1% . Casing follow-up technology is used in loose strata to prevent hole collapse.

Slurry preparation and jetting parameters: The water-cement ratio is usually 1:1, with a cement dosage of $200\ kg/m^3$. Admixtures are added to improve fluidity or early strength. High-pressure water pressure is $35\tilde{}40MPa$, slurry pressure is $10\tilde{}16MPa$, lifting speed is $8^{\circ}12$ cm/min , and rotation speed is $5^{\circ}10rpm$.

Handling of special cases: In case of slurry leakage, increase the slurry density or pour cement mortar; in severe cases, re-jetting is required. In case of interruption, if the interruption exceeds 20 minutes, re-jetting with an overlap of 30 cm is needed to ensure the continuity of the wall.

2.5 Quality Control and Effect Verification

Excavation inspection: Directly observe the continuity and lap quality of the wall.

Water pressure test: A permeability rate of $\leq 10Lu$ is considered qualified to ensure the anti-seepage performance meets the standard.

Strength test: Core sampling to test the compressive strength of the consolidated body.

3. APPLICATION OF HIGH-PRESSURE JET GROUTING TECHNOLOGY IN THE DANGER REMOVAL AND REINFORCEMENT PROJECT OF DAMA'AN RESERVOIR

3.1 Overview of Project Status

Dama'an Reservoir is a medium-sized reservoir in Qinzhou City, Guangxi, mainly for irrigation, integrating urban emergency water supply, flood control and other functions. The total storage capacity is 13.13 million m3, the effective storage capacity is 8.08 million m3, and the normal water level is 22.05m. The project was started in December 1957 and completed and put into use in August 1964. The reservoir hub project mainly consists of a dam (1 main dam and 5 auxiliary dams), a spillway, 1 irrigation outlet culvert, and 1 water supply outlet culvert. The main dam and all auxiliary dams of Dama'an Reservoir are homogeneous earth dams. The main dam has a maximum height of 18.1m, a crest length of 101.4m, and a crest width of 6.0m. The height of the auxiliary dams ranges from 4.73m to 17.32m. In February 2023, after review by the Dam Safety Management Center of the Ministry of Water Resources, it was agreed to identify the Dama'an Reservoir dam as a "Type III Dam", and danger removal and reinforcement will be carried out to eliminate engineering safety hazards and restore and improve the comprehensive utilization benefits of the reservoir.

3.2 Engineering Geological Conditions and Evaluation of the Dam

The main dam and all auxiliary dams are sourced from residual slope deposits, sandy gravel, and other materials near the project area, with varying particle sizes. Some soil layers consist of gravel and highly weathered argillaceous siltstone, distributed unevenly. The compaction degree of all dam fill ranges from 0.837 to 0.93, which does not meet the requirements of the "Design Specification for Rolled Earth-Rock Dams" (SL 274-2020). All dam fill is moderately compressible soil, with local areas of highly compressible soil. The permeability coefficient of the dam fill is mainly in the range of 10^{-3} ~10^{-5}, indicating moderate permeability, which does not meet the requirements specified in the "Design Specification for Rolled Earth-Rock Dams" (SL 274-2020). Based on experience, the seepage deformation mode of the dam fill is all piping.

The foundations of the main dam and all auxiliary dams are mainly composed of argillaceous siltstone from the fourth formation of the Lower Silurian Liantan Group (S11nd) and Quaternary (Q) strata. The gravel-containing silty clay is in a plastic to hard plastic state, with a gravel content of $10 \sim 15\%$ and a particle size of approximately $1\ \text{cm} - 3\ \text{cm}$. The thickness of the layer in the riverbed area ranges from 0.5m to 1.8m, and the thickness at the left and right dam shoulders is approximately 0.5m to 2.5m. The gravel-containing clay layers in the main dam foundation and dam shoulders are basically moderately permeable layers, and there are certain seepage problems in the contact zone of the dam foundation (shoulder).

3.3 Construction of Dam High-Pressure Jet Grouting

According to the characteristics of the Dama'an Reservoir Project, the triple-tube method is selected for high-pressure jet grouting construction. First, setting out and positioning are carried out according to the construction drawings. The nozzle diameter is $1.8 \sim 2\ \text{mm}$. For each hole, drilling is first performed from the grouting platform on the dam crest. After reaching the design depth, the jet pipe is lowered to the bottom of the hole through the dam body into the bedrock. The jet grouting operation is carried out from bottom to top following the steps of first supplying air, then water, then grout, and rotating the jet pipe in place until reaching the design pile top elevation. After the jet grouting of each hole is completed, backfilling into the hole is performed in a timely manner to ensure the compaction of the pile top.

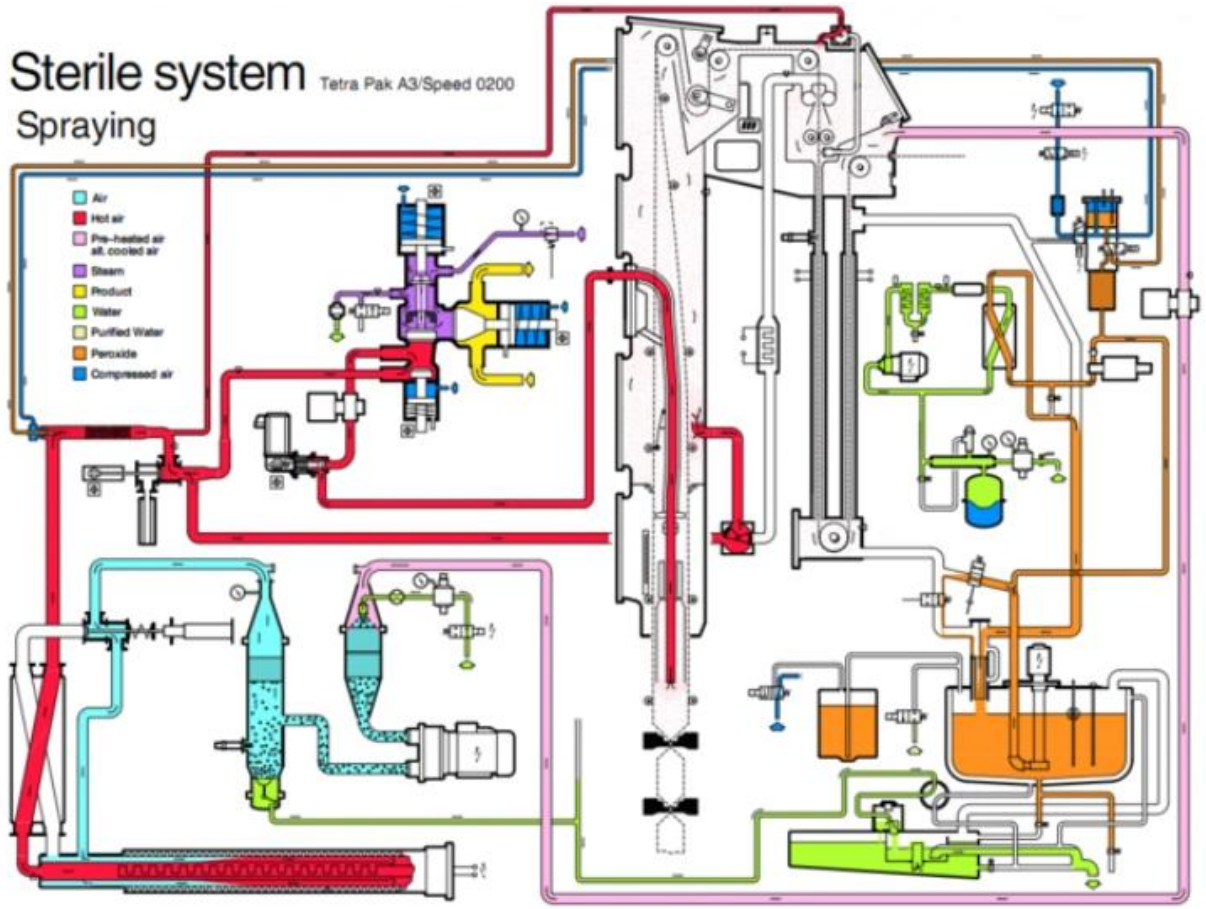

Figure 1: High pressure spray process flowchart

3.3.1 Construction Procedure of High-Pressure Jet Grouting

To ensure project quality, the following operating procedures are adopted during construction.

On-site high-pressure jet test

Before jet grouting, check the high-pressure jet grouting equipment and pipeline system; their pressure and flow must meet the design requirements. There must be no impurities in the nozzle and grouting pipe, and the sealing rings of the grouting pipe joints must be in good condition.

After the drilling rig jet unit is in place, ensure the center of the vertical shaft type turntable is aligned, and the inclination of the formed hole does not exceed 1.0%. During construction, set out and position according to the pile positions specified in the drawings, with the allowable center error not exceeding 5cm. After the drilling rig forms the hole, insert the jet pipe to the predetermined depth, and only after passing inspection can high-pressure jet grouting be carried out.

During the lowering of the jet pipe and the rotary jetting process, take care to prevent the nozzle from being blocked. When disassembling or installing the grouting pipe, act quickly. The pressure and flow rate of water, air, and slurry must meet the design values; otherwise, pull out the pipe for cleaning before re-lowering and rotary jetting.

During rotary jetting, properly measure the pressure, flow rate, and slurry volume, and record each item as required. The rotation and lifting of the jet pipe must be continuous without interruption.

For deep rotary jetting, start grouting first before rotating and lifting to prevent the grouting pipe from twisting and breaking.

When mixing water slurry, the water-cement ratio shall be in accordance with the design requirements and shall not be changed arbitrarily. During the rotary jetting process, prevent cement slurry from settling and reducing concentration. The use of damp or expired cement is prohibited.

During the rotary jetting process, check and adjust the consistency of the cement slurry to ensure the designed water-cement ratio and pile quality. After construction, immediately pull out the grouting pipe and thoroughly clean the grouting pipe and grouting pump.

High-pressure jet grouting shall be carried out from bottom to top. During the grouting process, the rated pressure and grouting volume of the high-pressure grouting equipment shall meet the requirements of the construction drawings, and ensure the pipeline system is unobstructed and sealed. Air, water, and slurry shall be continuously delivered, and high-pressure jetting of cement slurry shall not stop or be interrupted.

During the test run of the triple-pipe equipment, the pressure of the high-pressure water pump shall be maintained at 20±2Mpa, the air pressure of the air compressor at 0.6MPa, and the pressure of the mud pump at 0.1~1MPa. During construction, first start the air compressor under no load, and after it operates normally, start the high-pressure pump under no load. Then, supply air and water into the hole simultaneously, gradually increasing the air volume and pump pressure to the specified values. After air and water flow smoothly, rotate the grouting pipe and start the grouting pump, first supply clean water into the hole. After the pump volume and pressure are normal, move the suction pipe of the grouting pump to the slurry storage barrel and start grouting. Only after estimating that the front of the cement slurry has flowed out of the nozzle can the grouting pipe start to be lifted for bottom-up jet grouting.

Cement slurry shall be strictly filtered to prevent nozzle blockage during jetting operations.

Regularly test the density of cement slurry. When the water-cement ratio of the slurry is 1:1 and 1:1.5, the corresponding slurry densities are 1.5g/cm³ and 1.37g/cm³ respectively. If the slurry density exceeds the above indicators during construction, stop jetting immediately, adjust it to the normal range, and then continue jetting.

Before refreshing construction after a stoppage to any reason, lower the spray head by 30cm, perform overlapping jetting treatment, and then continue lifting upward and jet smoothing. Record the interruption depth and time. If the shutdown exceeds 3 h , clean the pump body and slurry delivery pipeline before continuing construction.

During construction, regularly check the pressure of the mud (water) pump, slurry flow rate, wind pressure and air volume of the air compressor, drilling rig rotation speed, lifting speed, and slurry consumption. When the measured slurry volume exceeds the grouting volume by 20% or there is no slurry Slurry emission at all, handle it in a timely manner in accordance with the provisions of Article 3.4.15 of YSJ210-92 and YBJ43-92

During construction, collect slurry emission samples as instructed by the supervisor, and take no less than 6 groups of slurry emission test specimens for each main stratum.

After the jetting operation is completed, continuously backfill the emitted slurry into the hole until the slurry level is stable. When jetting in clay layers or silt layers, the emitted slurry shall not be backfilled.

3.3.2 Construction Parameters for Jet Grouting

(1) Selection of jet grouting equipment:

According to the design requirements of this project, the high-pressure jet grouting pressure is 28-32Mpa. To ensure the design pressure, the main mechanical equipment to be used in this project includes a high-pressure water pump: GPBW type high-pressure water pump with a design pressure of 38Mpa, a displacement of 156L/min, and a power of 90kW. This water pump has a compact structure, small volume, light weight, and high efficiency. The power end crankshaft adopts a flow needle contact, which has low temperature rise during long-term operation. It is an excellent power source for continuous operation high-pressure fine jet equipment and also an excellent equipment for foundation treatment.

The XPB-90D type high-pressure jet grouting pump is one of the key equipment in high-pressure jet grouting. This grouting pump has the characteristics of light weight, multi-purpose high pressure, fixed (or variable) displacement, and can pump both clear water and high-density slurry. Its comprehensive technical performance is at a leading level, with a maximum pressure of 65Mpa, a plunger diameter of 45mm, a reciprocating frequency of 180/min, a small number of plungers, and a plunger stroke of 120mm.

VY-9/7-a type air compressor, with a volume of $9m^3$/min, an exhaust pressure of 0.9Mpa, and a power of 75kW. High-pressure jet grouting trolley: GP1500-6 type hydraulic high-pressure jet trolley with a hydraulic walking chassis.

Slurry making machine (mixing machine): 200L horizontal automatic batching and slurry making machine.

(2) Selection of pressure:

The construction water pressure is selected as 35~38MPa, the water flow rate is 75L/min, the grout pressure is 0.5~MPa, the flow rate is 70L/min , the air pressure is 0.6MPa , and the air volume is 0.8m3/ min.

(3) Lifting speed:

During construction, the lifting speed is controlled at 12cm/min to avoid excessively fast lifting speed, which would reduce the diameter of the consolidated body, affect the degree of soil fragmentation by the jet water flow, cause some cohesive soil in the soil to be stirred and mixed with the grout in blocks, and reduce the strength of the consolidated body.

(4) Rotation speed:

To ensure project quality, the rotation speed is 10~15/min, which is adjusted appropriately according to the stratum conditions.

(5) Nozzle:

The nozzle is a key part of rotary jet grouting. When high-speed jet water flows, the kinetic energy carried by the nozzle is not only related to the pump pressure but also closely related to the geometric shape of the nozzle. During construction, the nozzle should be tested and inspected for each grouting hole to avoid nozzle blockage and ensure jet quality.

4. QUALITY INSPECTION AND ACCEPTANCE

4.1 Before high-pressure jet grouting operations, the following items shall be subject to quality inspection and acceptance

On-site stakeout results of pile positions, material test results, grout mix ratio test results, and borehole deviation rate.

4.2 During high-pressure jet grouting operations, the following items shall be subject to quality inspection and acceptance

Insertion depth of jet insertion pipe; on-site high-pressure jet grouting test results; process inspection of high-pressure jet operations; test results of grout bleeding specimens.

4.3 After the completion of high-pressure jet grouting construction, the following items shall be subject to quality inspection and acceptance

Plane position of high-pressure jet grouting piles (holes); verticality, continuity, uniformity and overlapping degree of the high-pressure jet grouting cut-off wall; strength, water permeability, corrosion resistance and durability of the high-pressure jet grouting consolidated body. The quality inspection of the high-pressure jet grouting consolidated body shall adopt methods such as excavation inspection, borehole coring, dynamic pile

testing, standard penetration test, load test and water pressure test in accordance with the requirements of the construction drawings, and shall comply with the provisions of Articles 4.0.1 to 4.0.3 of YSJ210-92 and YBJ43-92.

5. CONCLUSION

The Dama'an Reservoir danger removal and reinforcement project adopted the triple-pipe method of high-pressure rotary jet grouting technology according to its specific engineering geological conditions, achieved the quality effect meeting the construction contract conditions, and successfully passed the completion acceptance. Through the summary and analysis of successful case experience, high-pressure rotary jet grouting technology has a good application prospect.

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