EXPERIMENTAL STUDY ON CURTAIN REINFORCEMENT GROUTING FOR DAM FOUNDATION OF MIAOWEI HYDROPOWER STATION

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ABSTRACT

The dam foundation curtain reinforcement grouting project of Lancang River Miaowei Hydropower Station has complex geological conditions, difficult construction and high anti-infiltration requirements. This paper introduces the on-site curtain grouting test, comprehensively compares the cement grouting and cement + silica sol grouting schemes in the left and right shore test areas, analyzes the test results, and puts forward reasonable construction suggestions.

Keywords *: Miaowei Hydropower Station, High dam and high head and large water burst, Silica sol grouting material, Curtain reinforcement grouting, Experimental study*

1. PROJECT OVERVIEW

Miaowei Hydropower Station is located on the reach of Lancang River in Miaowei Lisu Township, Yunlong County, Dali Prefecture, Yunnan Province. The project mainly focuses on power generation and is also used for irrigation and water supply. The reservoir has the normal water storage level of 1408.00m and the corresponding storage capacity of 686 million m^{3,} including the regulation storage capacity of 165 million m^3. The total installed capacity of the power station is 1400MW (4 × 350MW). The project is a rated as first-class large-size 1 project. The permanent main building is a level 1 building, and the minor building is a level 3 building.

The gravelly soil core rockfill dam[1] has a top elevation of 1414.80m and a maximum dam height of 139.8m. Foundation curtain grouting is used for anti-infiltration of the dam foundation.

2. GEOLOGICAL CONDITIONS

The construction area of Miaowei Hydropower Station, located in the range of 6.5km from Wanba River to Danwu Trench, has the medium height mountain intrenched stream valley landforms. The mountains are generally north-north-west, and the valleys are composed of asymmetric “V” valleys and wider “U” valleys alternately, with the river bed elevation of 1306 - 1283m.

The construction area of the power station is located in the steep folded region east of Shuijing - Gongguo fault, and the overall occurrence of the rock formation is N5° - 20°W, NEE or SWW ∠ 75° - 90°. Toppling deformation develops in the region [2], and the inclination of the rock formation becomes gentle, 30° - 70°. Affected by multi-stage tectonic movements, faults, intra-layer staggered zones, and joints in the area are relatively developed. The dominant direction of the structural plane is NNE, and followed by NE. Controlled by the peculiar topography and geomorphology, formation lithology and geological structure characteristics in the area, unfavorable physical and geological phenomena such as debris flow, collapse, and toppling deformation in the project area are relatively developed.

3. KEY AND DIFFICULT POINTS OF THE PROJECT

The geological conditions of the dam foundation of Miaowei Hydropower Station are complex. Metamorphic sand and slate are interbedded and unevenly distributed. After the early anti-infiltration treatment, larger cracks have been generally filled, small cracks and micro-cracks have developed, and the effect of ordinary cement grouting is dissatisfactory[3]. The major key and difficulties in the construction of this project: The first is how to solve the groutability of the micro-crack stratum and ensure the grouting effect, and the second is to solve the problem with the construction technology of steep dip-fissure stratum and the silica sol grout grouting.

4. CONSTRUCTION TECHNOLOGY AND METHODS

4.1 Layout of construction holes in the left shore test area

The left shore curtain grouting test area is positioned in the left shore slope corridor, with the location of dam 0 + 197.375m - dam 0 + 209.375m, and is arranged on the curtain grouting axis. The test area uses a single row with a hole distance of 1.5m. For the details of the curtain grouting hole layout, see 1.

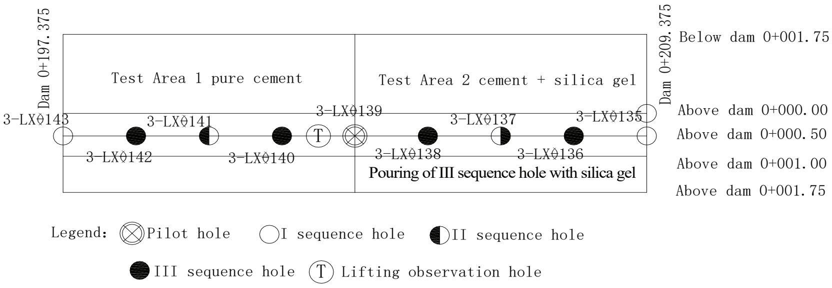

Figure 1 : Hole layout of the left shore reinforcement curtain grouting test area

4.2. Arrangement of construction holes in the right shore test area

The right shore curtain grouting test area is selected in the right shore 1368 grouting adit, located at the dam 0 + 564.00m - dam 0 + 572.00m, and arranged in the middle of the original two rows of curtains, with the pile number of 0 + 000.75m above the dam. The test area uses a single row with a hole distance of 1.0m. For the details of the curtain grouting hole layout, see Figure 2.

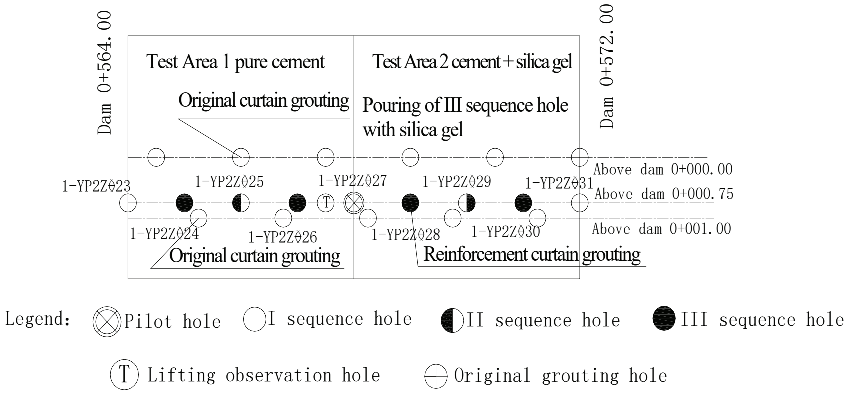

Figure 2 : Hole layout of the right shore reinforcement curtain grouting test area

4.3 Construction materials

4.3.1 *Cement*

P.O42.5 ordinary Portland cement is used for the reinforcement curtain grouting. The cement fineness is required to pass through a 80μm square hole sieve, with weight of screen residue not more than 5%. Other property indicators meet the requirements of the standard GB 175-2007.

4.3.2 *Silica sol slurry*

Silica sol material for grouting is independently developed by Sinohydro Foundation Engineering Co., Ltd. The main properties of the silica sol material are shown in Table 1.

Table 1 : Main properties of silica sol materials

Item	Conditions or requirements	Technical index control
Viscosity (mPa·s)	20℃ (after blending)	1.0 - 4.5
pH value	Grout	9 -10
Density (kg/L)		1.00 -1.20
Color	Slurry	Colorless, uniform and transparent
Odor	Slurry	Tasteless
Toxicity		Non-toxic
Grout operation time		3min -120min
Sufficient curing time		2h -24h

In this test, M-I and M-II type grouts with different gelation times and properties were selected, configured into A and B slurries at the slurrying station, stored in corresponding containers, and transported to the site for pouring.

4.4 Grouting construction

4.4.1 *Grouting method*

Cement and silica sol grouting holes use the ascending segmented packing grouting method.

4.4.2 *Orifice tube casting*

The orifice section of the cement grouting hole first undergoes packing grouting, and the orifice tube is cast. The orifice tube is buried in the bedrock to a depth of 2m, and the coagulation time is 72h. After the silica sol grouting at the orifice segment of the silica sol grouting hole is completed, the orifice tube is cast.

4.4.3 *Segment length and pressure*

The length of the first section of each grouting hole is 2m, the second segment is 3m, and the length of the following hole segments is 5m. In special cases, the segment can be shortened or lengthened appropriately, but should not be greater than 8m. Refer to Table 2 for cement grouting segment length and pressure, and refer to Table 3 for chemical grouting segment length and pressure.

Table 2 : Table of grouting pressure in each stage of cement grouting

Stage		1	2	3	4	5	6
Hole depth (m)		0 - 2	2 - 5	5 - 10	10 -15	15 -20	> 20
Grouting pressure (MPa)	I sequence hole	0.6	0.8	1.0	1.5	1.8	2.0
	II sequence hole	1.0	1.2	1.5	1.8	2.0	2.5
	III sequence hole	1.5	1.8	2.0	2.2	2.5	2.5

Table 3 : Table of grouting pressure in each stage of chemical grouting

Stage		1	2	3	4	5	6
Hole depth (m)		0 - 2	2 - 5	5 - 10	10 -15	15 -20	> 20
Grouting pressure (MPa)	III sequence hole	1.0	1.0	1.0	1.0	1.0	1.0

4.4.4 *Grout ratio and pouring water-cement ratio*

(1) In cement grouting, six levels of water-cement ratios of 5: 1, 3: 1, 2: 1, 1: 1, 0.8: 1, and 0.5: 1 are used for pouring. The grout ratio should be changed from thin to thick during grouting, and the water-cement ratio should be 5: 1. The principle of grout transformation is as follows:

  (a) During grouting, the water-cement ratio must not be changed when the grouting pressure remains unchanged and the injection rate continues to decrease, or when the injection rate is constant and the pressure continues to increase.

  (b) When the injection volume of a certain level of grout has reached more than 300L, or the grouting time has reached 30min, but the grouting pressure and injection rate have not changed or the change is not significant, a thicker level of pouring should be used.

  (c) When the injection rate is greater than 30L/min, the grout can be thickened by skipping a level in accordance with specific conditions.

(2) Principle of silica sol grout transformation

  (a) MI-type grout is used at the beginning of pouring. When the grouting pressure remains unchanged and the injection rate continues to decrease, or when the injection rate is constant and the pressure continues to increase, the type of grout must not be changed and the pouring should be continued.

  (b) When the MI -type grout reaches 100 L/m, the grouting pressure and injection rate have not changed or the change is not significant, it should be changed to M-II type grout for pouring.

4.4.5 *Grouting end standard*

(1) The end conditions of each grouting segment of cement grouting: Under the specified pressure of the grouting segment, when the injection rate is not greater than 1 L/min, pouring continues for 30 minutes and then can be ended.

(2) Ending standard of silica sol grouting: After the injection rate is not greater than 1 L/min at the design pressure, pouring continues for 30 minutes or the gel time is reached.

4.4.6 *Hole sealing*

Cement grouting holes are sealed using the “full-hole grouting and sealing method”. For silica sol grouting holes, the bottom of hole is cleaned after the end of the grouting, and the holes are sealed according to the cement grouting hole method.

5. GROUTING TEST RESULTS AND ANALYSIS

5.1 Permeation rate of rock mass

In order to understand the permeation rate of the rock mass before grouting in the test area, prior to cement grouting, a pressure water test was performed on each grouting segment, and the leakage of the rock mass was analyzed through the change to permeation rate before grouting of sequence holes.

Table 4 : Results of permeation rate before grouting of sequence holes in the right shore test area

Location	Hole sequence	Number of holes	Average permeation rate (Lu)	Frequency of permeation rate before grouting (number of segments in each interval/frequency %)								Remark
				Total number of segments	≤1	1 - 3	3 - 5	5 - 10	10 - 50	50 - 100	> 100	
Right shore test area	I	3	7.50	30	9/30.0	6/20.0	4/13.3	6/20.0	2/6.7	2/6.7	1/3.3	
	II	2	4.65	20	3/15.0	6/30.0	4/20.0	6/30.0	1/5.0	0/0	0/0	
	III	4	2.54	40	13/32.5	18/45.0	3/7.5	5/12.5	1/2.5	0/0	0/0	
	Total	9	4.90	90	25/27.8	30/33.3	11/12.2	17/18.9	4/4.4	2/2.2	1/1.1	

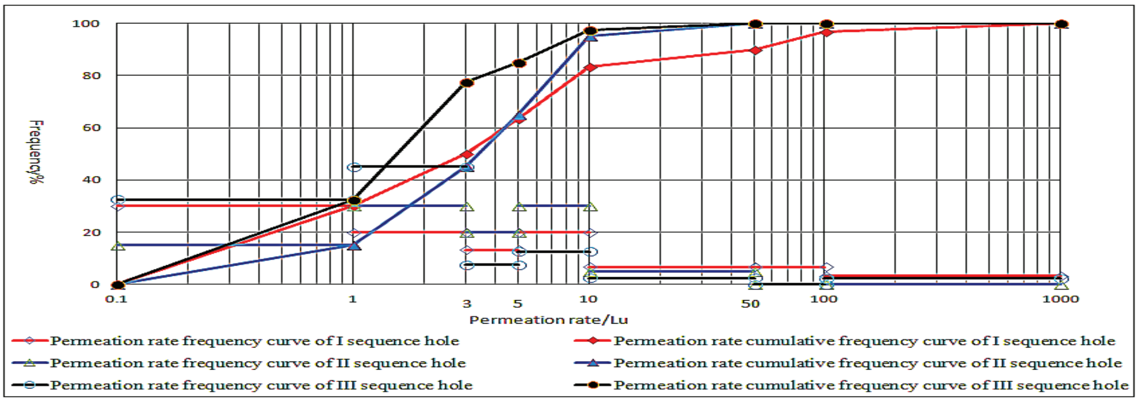

Figure 3 : Permeation rate frequency curve of cement grouting of each sequence hole in the right shore test area

As can be seen from Table 4 and Figure 3 above : With the construction of grouting of I, II, and III sequence holes, the permeation rate of the right shore test area was 7.5Lu, 4.65Lu, and 2.54Lu, respectively, and the diminishing regularity was significant, in which the permeation rate of the II sequence hole before grouting was 38.0% lower than that of the I sequence hole, and the permeation rate of the III sequence hole before grouting was 45.4% lower than that of the II sequence hole.

Table 5 : Results of permeation rate before grouting of sequence holes in the left shore test area

Location	Hole sequence	Number of holes	Average permeation rate (Lu)	Frequency of permeation rate before grouting (number of segments in each interval/frequency %)								Remark
				Total number of segments	≤1	1 - 3	3 - 5	5 - 10	10 - 50	50 - 100	> 100	
Right shore test area	I	3	1.84	45	18/40.0	21/46.7	3/6.7	3/6.7	0/0	0/0	0/0	
	II	2	5.37	30	8/26.7	4/13.3	4/13.3	10/33.3	4/13.3	0/0	0/0	
	III	4	2.20	60	19/31.7	25/41.7	10/16.7	6/10.0	0/0	0/0	0/0	
	Total	9	3.14	90	45/50.0	50/55.6	17/18.9	19/21.1	4/4.4	0/0	0/0	

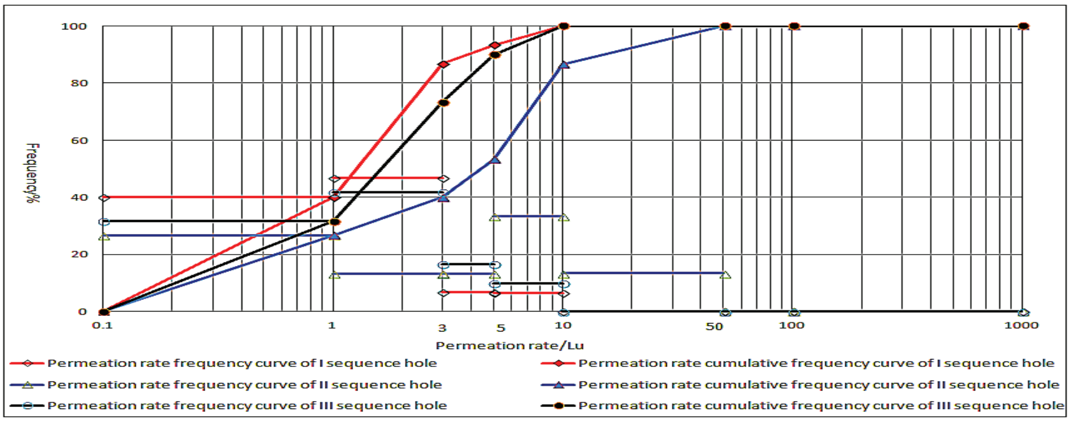

Figure 4 : Permeation rate frequency curve of cement grouting of each sequence hole in the left shore test area

As can be seen from Table 5 and Figure 4 above : With the construction of grouting of I, II, and III sequence holes, the permeation rate of the left shore test area was 1.84Lu, 5.37Lu, and 2.20Lu, respectively, the diminishing regularity was not significant, but that of III sequence holes was lower than that of II sequence holes; the permeation rate of the II sequence hole before grouting was 191.8.0% higher than that of the I sequence hole, and the permeation rate of the III sequence hole before grouting was 59.0% lower than that of the II sequence hole.

By means of analysis of permeation rate, the overall permeation rate of the test area was smaller, the diminishing regularity was significant in the right shore, but not significant in the left shore, indicating that the test area was featured by relatively small cracks and micro-cracks and less large cracks.

5.2 Cement unit injection volume

See Table 6 for the results of the frequency intervals of cement unit injection volume.

Table 6 : Summary of results of unit injection volume frequency of each sequence hole in the right shore test area

Location	Hole sequence	Number of holes	Grouting Length (m)	Unit Injection volume (kg/m)	Unit ash injection volume (kg/m) frequency (number of segments in each interval/frequency %)					
					Total number of segments	<10	10 - 50	50 - 100	100 - 500	> 500
Right shore test area	I	3	144	57.37	30	10/33.3	9/30.0	6/20.0	5/16.7	0/0
	II	2	96	52.91	20	6/30.0	7/35.0	4/20.0	3/15.0	0/0
	III	2	100	41.61	22	9/40.9	9/40.9	1/4.5	3/13.6	0/0
	Total	7	340	51.47	72	25/34.7	25/34.7	11/15.3	11/15.3	0/0

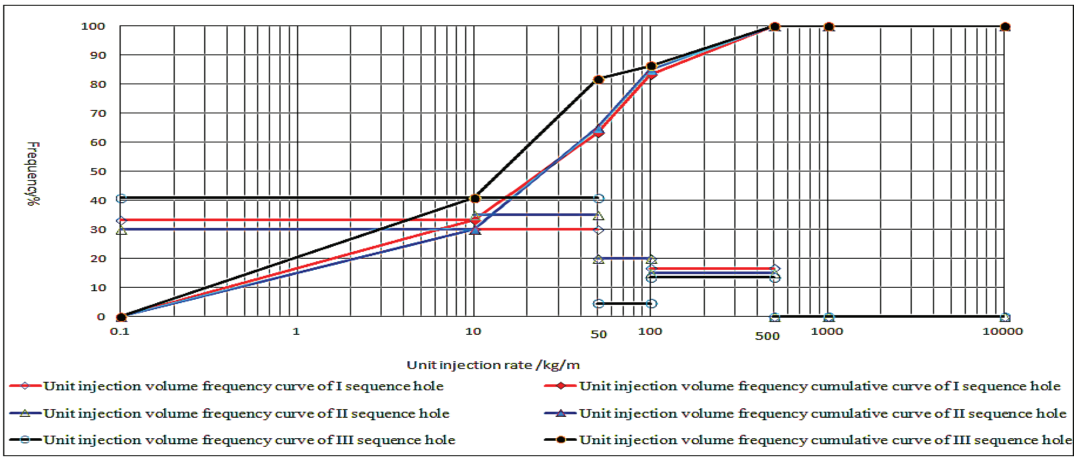

Figure 5 : Unit injection volume frequency curve of cement grouting of each sequence hole in the right shore test area

The unit injection volume can reflect whether the process technology, grouting material, and grout ratio used in the grouting process are reasonable. Generally, the unit injection volume gradually decreases with the hole sequence[5]. According to Table 6 and Figure 5, the injection volume of III sequence hole decreased by 21.36% compared to the II sequence hole, and that of II sequence hole decreased by 7.77% compared to the I sequence hole. 57.37 kg/m for I sequence hole, > 52.91kg/m for II sequence hole, and > 41.61kg for III sequence hole. With the increase of hole sequence, the cement unit injection volume shows a gradual decrease, complying with the diminishing regularity of grouting.

Table 7 : Summary of results of unit injection volume frequency of each sequence hole in the left shore test area

Location	Hole sequence	Number of holes	Grouting length (m)	Unit injection volume (Kg/m)	Unit ash injection volume (kg/m) frequency (number of segments in each interval/frequency %)					
					Total number of segments	<10	10 - 50	50 - 100	100 - 500	> 500
Left shore test area	I	3	211.5	26.44	45	15/33.3	25/55.6	2/4.4	3/6.7	0/0
	II	2	137.8	39.74	30	10/33.3	6/20.0	14/46.7	0/0	0/0
	III	2	137.8	22.94	32	13/40.6	15/46.9	3/9.4	1/3.1	0/0
	Total	7	487.1	29.97	107	38/35.5	46/43.0	19/17.8	4/3.7	0/0

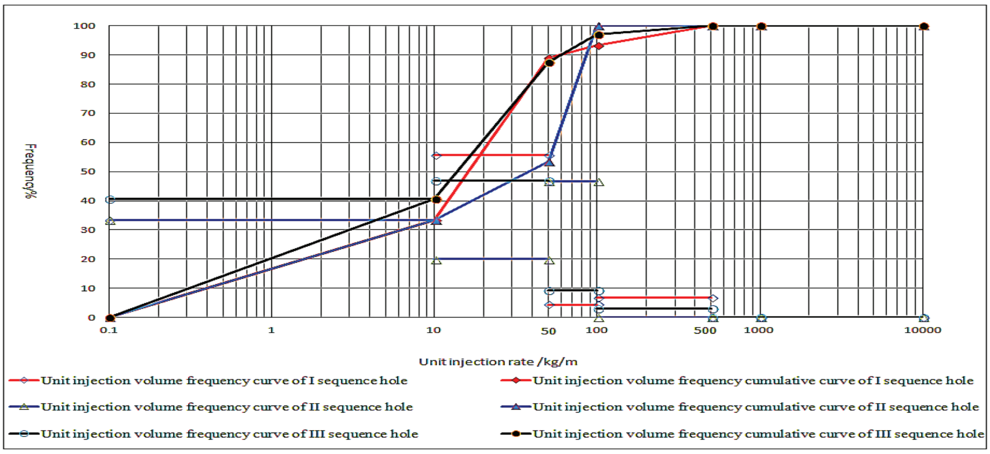

Figure 6 : Unit injection volume frequency curve of cement grouting of each sequence hole

According to Table 7 and Figure 6, the injection volume of III sequence hole decreased by 42.27% compared to the II sequence hole, and that of II sequence hole decreased by 50.30% compared to the I sequence hole. 26.44kg/m for I sequence hole, >39.74kg/m for Ⅱ sequence hole, and >22.94kg for III sequence hole. With the increase of the hole sequence, the cement unit injection volume did not change significantly, not conforming to the diminishing regularity of grouting. The left shore grouting test area has good geological conditions. The cracks in metamorphic sand and slate are mainly micro-cracks and small cracks. The grouting of cement grout can solve some of the problems of small cracks, and the groutability of cement grout is limited.

5.3 Silica sol unit injection volume and permeation rate

Table 8 : Results of silica gel grouting of III sequence holes in the right shore

Location	Hole sequence	Number of holes	Average permeation rate (Lu)	Permeation rate frequency before grouting (number of segments in each interval/frequency %)								Remark
				Total number of segments	≤1	1 to 3	3 to 5	5 to 10	10 -50	50 -100	> 100	
Right shore test area	III (cement)	2	2.94	22	5/22.7	11/50.0	2/9.1	3/13.6	1/4.5	0/0	0/0	
	III (Silica sol)	2	2.05	18	8/44.4	7/38.9	1/5.6	2/11.1	0/0	0/0	0/0	
	Total	4	2.50	40	13/32.5	18/45.0	3/7.5	5/12.5	1/2.5	0/0	0/0	

Table 9 : Results of cement silica sol grouting of III sequence holes in the left shore

Location	**Hole sequence**	**Number of holes**	**Average permeation rate (Lu)**	**Permeation rate frequency before grouting (number of segments in each interval/frequency %)**								**Remark**
				Total number of segments	**≤1**	**1 - 3**	**3 - 5**	**5 - 10**	**10 - 50**	**50 - 100**	**> 100**	
Left shore test area	III (cement)	2	2.50	32	9/28.2	13/40.6	5/15.6	5/15.6	0/0	0/0	0/0	
	III (Silica sol)	2	1.88	28	10/35.7	12/42.9	5/17.9	1/3.5	0/0	0/0	0/0	
	Total	4	2.19	60	19/31.7	25/41.7	10/16.7	6/10.0	0/0	0/0	0/0	

Table 10 : Statistics of permeation rate and unit injection volume of silica sol in III sequence hole pouring

Permeation rate of III sequence hole (Lu)	≤1	1 - 3	3 - 5	5 - 10	10 -50	50 -100	> 100
Right shore silica sol slurry Average injection volume (L/m)	19.80	95.84	174.67	61.78	/	/	/
Left shore silica sol slurry Average injection volume (L/m)	10.51	39.86	48.18	123.19	/	/	/

As can be seen from Table 8, Table 9, and Table 10, in the left and right shores, the proportion of hole segments with the permeation rate of Ⅲ sequence hole before grouting < 10Lu is greater than 90.0%. In the right shore test area, with the increase of permeation rate, the unit injection volume of the silica sol gradually increases, the ascending relationship between the permeation rate and the unit pouring rate is obvious, and silica sol can be poured well.

Table 11 : Statistics of permeation rate before and after grouting

1-YP2 (Z) -28	**Stage**								
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Permeation rate before grouting (Lu)	0.89	1.70	2.73	1.74	0.88	7.65	5.49	0.74	2.96
Permeation rate after grouting (Lu)	0.41		0.44	0.44	0.21		0.02	0.53	
Descending rate %	75.88		83.88	74.71	97.25		99.64	82.09	

As can been seen from Table 11, Comparison of the permeation rate before and after grouting of 1-YP2 (Z) -28 hole, the pressurized-water permeation rate after grouting is less than 1Lu, and the descending rate is 74.71% - 99.64%, demonstrating that under the formation conditions, pouring of fine cracks with silica sol has a better effect.

6. DETECTION AND EVALUATION OF GROUTING EFFECT

6.1 Inspection hole pressurized water test

Qualified if not more than 3Lu as per the design requirement of Miaowei Project. The permeation coefficient of foundation curtain grouting stratum of Miaowei Dam is 10^{-5} -10^{-3} cm/s (about 1 -150Lu). For the results of inspection holes, see Table 12. The results in the right shore cement grouting area and silica sol grouting area are all acceptable, and the effect of silica sol pouring area is better than that of the cement pouring area. Table 13. The maximum permeation rate of the left shore cement grouting area is 3.78Lu, and there is a segment of 3.37Lu as the contact segment. All other holes are qualified. The pass rate in the cement grouting area is 85.7%. The maximum pass rate in the silica sol grouting area is 100%.

Table 12 : Pressurized water test results of inspection holes in the right shore

Hole number	Hole segment	Lugeon value (Lu)
1-YP2 (Z) SZWJ-1 (Silica gel area)	1	0.91
	2	0.67
	3	0.39
	4	0.42
	5	0.63
	6	0.72
	7	0.82
	8	0.80
	9	1.01
	10	0.15
1-YP2 (Z) SZWJ-2 (Cement area)	1	0.74
	2	2.98
	3	1.50
	4	1.36
	5	0.45
	6	1.27
	7	1.16
	8	3.52
	9	0.20
	10	1.22

Table 13 : Pressurized water test results of inspection holes in the left shore

Hole number	Hole segment	Lugeon value (Lu)
3-LXSZWJ-1 (Silica gel area)	1	0.90
	2	0.48
	3	1.33
	4	0.83
	5	0.44
	6	0.58
	7	0.37
	8	0.45
	9	0.37
	10	0.62
	11	0.21
	12	0.80
	13	0.85
	14	1.37
	15	1.42
3-LXSZWJ-2 (Cement area)	1	3.37
	2	0.39
	3	1.24
	4	0.83
	5	1.40
	6	0.04
	7	1.22
	8	1.11
	9	0.78
	10	1.50
	11	1.79
	12	3.78
	13	2.20
	14	1.56

6.2 Core sample inspection

Figure 7 : Core diagram of cement grouting hole

Figure 8 : Core diagram of silica sol grouting hole

With the completion of the grouting construction, the grout is injected into the fractures, and the overall trend of the core of the inspection hole from top to bottom is more and more complete. There are traces of cement grouting impregnation in the core part of the cement grouting inspection hole, as shown in Figure 7 (left). As can be seen clearly, there are obvious new and old cement pastes on the sand slate. Filling inspection hole silica core after destruction of the core breaks the natural joint surface micro-cracks have a silica filled fracture traces in FIG 8 in the left.

6.3 Evaluation of grouting effect

On the basis of the core in the inspection hole, the pastes in the core, and inspection hole pressurized water test results, the grouting effect is very obvious; there are hole segments where the pressurized water test permeation rate more than 3Lu in the cement grouting area, which are primarily caused by the complexity of the high dip angle fractures of sand slate, and the direction and range of grout diffusion are limited.

In general, the grouting test has achieved good results, providing valuable data and experience for grouting and processing of similar strata in the project.

7. CONCLUSIONS AND RECOMMENDATIONS

(1) The site selected for the grouting test area can basically reflect the overall geological conditions of the dam foundation under the different mountain geological conditions in the left and right shores, and is highly representative.

(2) The comprehensive comparison of cement grouting and cement + silica sol in the test area in the left and right shores indicates that the effect of cement + silica sol is better. A large permeation rate is still present in some strata. To achieve a better effect, it is recommended to conduct cement grouting processing or open a new hole before silica sol pouring. Hole distance of 1m is better.

(3) The silica sol grouting material, a non-toxic, safe and environmentally friendly chemical grouting material, is applied to the dam foundation curtain of Miaowei Hydropower Station, where metamorphic sand and slate are interbedded and distributed unevenly, and steep angles of fissures develop, has successfully solved the difficult problems in project construction. Satisfactory results have been achieved in the test.

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