Study and application of heat preservation and crack control measures for gravity dam in severe cold regions

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Abstract. During the concrete pouring process, the long downtime would weaken the bonding strength between old and new concrete layers. The bonding parts would like to form horizontal cracks, especially winter intermittent surface in the severe cold region, of which cracks would easily propagates from surface to inside, even through the concrete, seriously affects the security of dam. This paper takes the sediment storage dam of the down reservoir of Hohhot pumped storage power station as a case, the heat preservation and crack control measures of overwintering area have been analyzed. To avoid the occurrence of cracks of overwintering layer during winter and according to the site or local material, this paper draws up two schemes. Scheme I: taking the water storage to preserve heat; Scheme II: 5cm thick polystyrene insulation (which can be used as temporary heat preservation measures normally) and 15cm thick straw and 30cm thick corn straw +2 layer water proof cloth. According to the simulation of the two schemes, the results shows that: scheme I exist "chilling effect" and the local stress is too high, while both the temperature and stress conditions of scheme II meet the requirements for overwintering. After overwintering period, the construction of the dam continues. To ensure the quality of concrete near the overwintering layer, the upper and lower temperature difference and the highest temperature should be controlled and the crack prevention of concrete should be took. According to the construction conditions, the similar experience in project site and relevant requirements of crack prevention, this paper makes three schemes. Scheme I: control the upper pouring new concrete pouring layer thickness, pouring temperature, intermittent, water and temporary insulation and return to construction in late-April; Scheme II: Taking all measures of Scheme I and heating the old concrete layer; Scheme III: Taking all measures of Scheme II and return to construction in mid-May. The simulation results show that Scheme I occurs upper and lower temperature difference and the existence of tensile stresses exceed the standard phenomenon, while Scheme II and III are feasible. After two consecutive 2011~2013 overwinters test, the implementation of heat preservation and crack control measures of overwintering layer concrete of the sediment storage dam of the down reservoir of Hohhot pumped storage power station works well, which can provide a reference for the similar problems in other engineering.

Introduction

Generally gravity dams of large and medium hydropower stations need more than one year to complete construction because of its large volume of concrete. In severe cold regions due to weather restrictions, winter should be shut down intermittently, resulting in bonding issues between new and old concrete layers and overwintering layer issues. During the concrete pouring process, the long downtime would weaken the bonding strength between old and new concrete layers. The bonding parts would like to form horizontal cracks, especially winter intermittent surface in the severe cold region. When the horizontal cracks occur on the upstream surface, reservoir impoundment resulting vertical compressive stress below the seam internal water pressure, cracks would easily extended to the downstream face of the dam, causing hydraulic fracture[1], seriously affect the security of dam. When the horizontal cracks occur in the water level fluctuation zone in severe regions, it is easily to produce concrete freeze-thaw damage, seriously affect the life of the dam. This

paper takes the sediment storage dam of the down reservoir of Hohhot pumped storage power station as a case, the heat preservation and crack control measures for gravity in severe cold regions have been analyzed.

Hohhot pumped storage power station locates in the area of DaQing mountain, northeast of Hohhot City in Inner Mongolia Autonomous Region, where belongs to the severe cold area, climate has the characteristics of long winter and short summer, winter and summer changes dramatically, large temperature difference, high evaporation. The winter is long and cold, permafrost period of up to five months. In dam area the annual average temperature is 6.3°C, the monthly mean temperature of July is 22.4°C and -12.2°C in January, the extreme maximum temperature is 38.5°C, the extreme minimum temperature is -32.8°C, the maximum wind speed is 20.0m/s.

The project's total installed capacity is 1200MW, and the size belongs large (1) type. The sediment storage dam of the down reservoir is a RCC gravity dam which used the "gold silver package" approach: 2.0m impermeable layer upstream and 3.0m protective layer downstream and 1.5m foundation cushion layer are all of normal concrete. Crest elevation is 1401m, the maximum height of 58m, crest length of 200m, the largest dam bottom width of 58m. The dam without longitudinal joints, only transverse joints, is divided into 12 sections, in addition to the right bank 1# dam section and the left bank 10#~12# dam sections transverse joint space is 14.0m, the rest of the dam is 18.0m.

Basic information

The cushion concrete (elevation 1343~1344.5m) of sediment storage dam is poured in mid-July 2011, pouring temperature of 15.2°C~20.5°C, the average atmospheric temperature of 24°C. The normal concrete and roller compacted concrete of elevation 1344.5~1347.5m are poured in late September, pouring temperature of 12.4°C~17°C, the average atmospheric temperature of 13.4°C. The normal concrete and roller compacted concrete of elevation 1347.5~1351.0m are poured in mid-October, pouring temperature of 7°C~15.5°C, the average atmospheric temperature of 10°C. The normal concrete and roller compacted concrete of elevation 1351.0~1352.5m are poured in late October, pouring temperature of 8°C~14°C, the average atmospheric temperature of 6.5°C. When pouring to elevation 1352.5m the construction of dam is shut down because of overwinter in early November.

The cooling water pipes are arranged to 1.0m (horizontal) $\times$ 0.9m (vertical) in cushion part, the other parts the cooling water pipes arranged 1.5m (horizontal) $\times$ 1.5m (vertical), water temperature averages 10°C, 13 ~ 25L / min, through the water time 20d. In late October 1351.5 ~ 1352.5m elevation pouring concrete is not disposed of cooling pipes.

In mid-November 2011, the construction of the upstream and downstream dam face permanent insulation measures is completed: the upstream surface of 5cm thick polyurethane + Rock Backfill, the downstream surface by spraying 8cm thick polyurethane +3cm thick polyester mortar.

The concrete mix proportion of the sediment storage dam of the down reservoir is shown in table 1.

Table 1   The main parameters of concrete mix proportion

No.	Position	Grade	Cement	Fly-ash	Water
①	Cushion and downstream of the dam site(less than elevation 1354m),Normal concrete,(t hird grade)	$C_{90}25$	166kg	64kg	104kg
②	Roller compacted concrete (third grade)	$C_{90}15$	72kg	108kg	90kg
③	Upstream and downstream of the dam site(higher than elevation 1354m),Normal concrete,(third grade)	$C_{90}25$	227kg	57kg	125kg

According to the test data and related information [2] [3] [4] of this project, thermodynamic parameters of the concrete is shown in Table 2 - Table 5.

Table 2   Thermodynamics parameters of concrete

No.	Thermal diffusivity $\alpha/(m^2/d)$	Thermal conductivity λ /(kJ/d•m•°C)	Specific heat c /(kJ/kg•°C)	Heat transfer coefficient β/(kJ/(m2•d•°C))	Linear expansion coefficient α $(10^{-6}/°C)$	Density ρ /(kg/m³)	Poisson's ratio ν	Adiabatic temperature rise (°C)	Elastic modulus E/ GPa
①	0.077	248	1.03	960	7.95	2510	0.167	$\theta(\tau) = 30\tau /(2.0 + \tau)$	$E = 38(1 - e^{-0.5\tau^{0.39}})$
②	0.086	251	0.97	960	7.69	2510	0.167	$\theta(\tau) = 16\tau /(4.0 + \tau)$	$E = 33(1 - e^{-0.52\tau^{0.5}})$
③	0.074	243	1.04	960	8.14	2470	0.167	$\theta(\tau) = 40\tau /(1.5 + \tau)$	$E = 43(1 - e^{-0.5\tau^{0.36}})$

Table 3 The maximum allowable tensile stress of concrete

No.	Age (d)	Elastic modulus (MPa)	Ultimate tensile value (×10-6)	Allowable tensile stress (MPa)
①	7	24.4	73	1.08
	28	33.5	86	1.75
	90	36.1	91	1.99
	180	37.1	93	2.09
②	7	24.4	-	-
	28	27.8	75	1.26
	90	30.7	86	1.6
	180	30.7	89	1.66
③	7	27.2	82	1.35
	28	38	93	2.14
	90	38.8	96	2.26
	180	39.8	97	2.34

Table 4 The maximum allowable vertical stress of concrete

No.	Age (d)	Axial tensile strength (MPa)	Allowable vertical stress (MPa)
①	7	1.47	0.59
	28	2.79	1.12
	90	3.14	1.26
	180	3.41	1.36
②	7	-	-
	28	1.37	0.55
	90	2.48	0.99
	180	2.73	1.09
③	7	1.72	0.69
	28	3.1	1.24
	90	3.49	1.4
	180	3.79	1.52

The overwintering layer surface (elevation 1352.5m) of sediment storage dam is in strong constrained zones, that concrete temperature control criteria is shown in Table 5.

Table 5 Concrete temperature control criteria

Name	Cushion concrete	RRC of inside	Normal concrete of upstream and downstream
Maximum allowable temperature	28.5℃	23℃	28.5℃
Upper and lower allowable temperature difference	16℃	15℃	16℃
Inside and outside temperature difference	20℃	20℃	20℃
Insulation standard KJ / (m2·d·℃)	≤38.8℃	≤38.8℃	≤38.8℃

Simulation and analysis of insulation measures for overwintering layer

When the sediment storage dam of the down reservoir of Hohhot pumped storage power station is poured to elevation 1352.5m, the construction of dam is shut down.

To avoid the occurrence of cracks of overwintering layer during winter and according to the site or local material, this paper draws up two schemes. Scheme I: taking the water storage to preserve heat; Scheme II: 5cm thick polystyrene insulation + 15cm thick straw and 30cm thick corn straw +2 layer water proof cloth.

According to the formula (1) [5], surface equivalent heat transfer coefficient of concrete after insulation is calculated: Scheme I is 34 KJ / (m2·d·℃); Scheme II is 32 KJ / (m²·d·℃). The results show that both the insulation schemes meet the requirements.

$$\beta = 1 / (\frac{1}{\beta_0} + \frac{\sum h_i}{\lambda_i k_1 k_2}) \qquad (1)$$

λ_i——thermal conductivity of insulation materials，water：2.1 KJ/(m•h•k)，ice：2.2 KJ/(m•h•k)，straw and corn straw：0.51 KJ/(m•h•k)，polystyrene insulation：0.1 KJ/(m•h•k)；

β_0——surface equivalent heat transfer coefficient of concrete without insulation, 40 KJ/(m·h·k);

h_i——insulation thickness, m;

k_1——wind speed correction factor, 1.3;

k_2——humidity correction factor, wet materials is 3~5, dry materials is 1.

According to the 2011 record of dam concrete construction and concrete thermodynamic parameters, the heat preservation Schemes I&II are simulated by the 3-D finite element. The results are been shown in Table 6 and Table 7.

Table 6 Temperature results during the winter

Scheme	I		II	
Place	center of overwintering layer	boundary of overwintering layer	center of overwintering layer	boundary of overwintering layer
The min temperature	2.7℃	1.3℃	4.8℃	3.3℃
The max temperature	17℃	17℃	17.5℃	17.5℃
Inside and outside temperature difference	14.3℃	15.7℃	12.7℃	14.2℃
Inside and outside temperature control standards	≤20℃	≤20℃	≤20℃	≤20℃
Meet requirements?	Yes	Yes	Yes	Yes

Table 7   Stress results during the winter

Scheme	I	II			
Place	center of overwintering layer	center of overwintering layer	1350.5~1352.5 m	1347.5~1350.5 m	1344.5~1347.5 m
The max tensile stress	1.2Mpa	0.82Mpa	1.2Mpa	1.15Mpa	1.34Mpa
Time	water storage for preservation	February of second year	the end of winter		
Age	14d	90d	180d		
Allowable tensile stress	0.9Mpa	1.6Mpa	1.66Mpa		
Meet requirements?	No	Yes	Yes		

Table 6 shows that: Under the condition of Scheme I and Scheme II, the lowest temperatures of overwintering layer are higher than 0°C during the winter; Inside and outside temperature difference of the overwintering layer is 12.7°C~15.7°C, both of which meet inside and outside temperature control standards. So, both of the schemes are feasible, from the perspective of the temperature difference between inside and outside.

Analysis from the perspective of temperature stress during the winter in Table 7 shows that, under the condition of heat preservation Scheme I, the maximum tensile stress, at the time of storage, in the central portion of the overwintering layer is 1.2 M Pa, which exceeds the allowable tensile stress. Therefore, Scheme I does not meet the heat preservation requirements. The reasons are that: concrete of overwintering layer is poured in late October, the heat preservation measure of water storage is completed in mid-November according to temperature environment and technical requirements. Temperature of internal concrete of the overwintering layer with the age of 14d is still very high, while water temperature is only 7~8°C, which results the "chilling effect". In addition that, because of lower anti-crack strength of early age concrete, excessive tensile stress occurs in the central portion of the overwintering layer.

Under the condition of heat preservation Scheme II, the maximum tensile stress is 0.82 M Pa which occurs at the central portion of the overwintering layer during winter, and it meets the age (90d) concrete allowable tensile stress requirements. Although the maximum tensile stress in the central portion of the overwintering layer reaches 1.15~1.34MPa at the end of the winter time, it meets the age (180d) concrete tensile stress requirements, whose anti-crack strength is 1.66MPa.

According to the simulation and analyses of inside and outside temperature difference and temperature stress of Scheme I & II: both of the schemes meet the requirements of inside and outside temperature difference, Scheme I does not meet the requirements of allowable tensile stress, while Scheme II meets.

In conclusion, Scheme II is chosen as the heat preservation measure of the overwintering layer concrete in sediment storage dam, that is 5cm thick polystyrene insulation + 15cm thick straw and 30cm thick corn straw +2 layer water proof cloth.

Simulation analysis for crack prevention measures at overwintering layer

The concrete of sediment storage dam continued pouring after 2011~2012 overwinter. In order to ensure the quality of concrete and avoid the cracks at the bounding between new and old concrete, the crack prevention of concrete should be taken to control the upper and lower temperature difference and the highest temperature according to the technique request for temperature control of sediment storage dam. On the basis of site construction conditions, similar engineering experience and the technique request for temperature control, three different schemes of crack prevention measures at overwintering layer were decided.

Scheme I: The new concrete parameters were controlled as follows. The layer thickness was 3.0m, the pouring temperature was 12°C, the layer intermittence was 7 days, the 2.5cm thick expanded polystyrene board was used as temporary insulation measure. The cooling water pipes are arranged to 1.5m (horizontal) × 1.5m (vertical) in roller compacted concrete, and the cooling water pipes are arranged to 1.0m (horizontal)

× 0.9m (vertical) in normal concrete, 1m far from the dam surface. The groundwater that temperature range from 8°C to 10°C was used as cooling water. The cooling water flow was controlled to be 40 L/ min after concrete pouring 4~5 days, then the water flow decrease to 18~20 L/ min until concrete pouring 18~20 days, and return to construction in late-April.

Scheme II: Taking all measures of Scheme I and heated the old concrete layer (two layers below the overwintering layer, 1347.5 ~ 1352.5m elevation) by cooling pipe in the dam. Water temperature range from 20°C to 23°C, water continued for 7 days (from new concrete 7 days after construction resume to pouring end), and return to construction in late-April.

Scheme III: Taking all measures of Scheme II, and return to construction in mid-May.

According to the concrete construction record of sediment storage dam, insulation measures during overwintering period and thermodynamics parameters of concrete, 3-D finite element simulation on the three different schemes of crack prevention measures at overwintering layer was calculated. The calculation results were listed in table 8~12.

Table 8   The highest temperature results of new concrete after return to construction

Scheme	I		II		III	
Position	1352.5~ 1355.5m	1355.5~ 1358.5m	1352.5~ 1355.5m	1355.5~ 1358.5m	1352.5~ 1355.5m	1355.5~ 1358.5m
Highest temperature of RCC	18.8°C	19.4°C	19.4°C	19.9°C	20.9°C	21.7°C
Allowable temperature of RCC	23°C	23°C	23°C	23°C	23°C	23°C
Meet requirements?	Yes	Yes	Yes	Yes	Yes	Yes
Highest temperature of normal concrete	24.4°C	26.4°C	24.6°C	26.6°C	25.8°C	28.1°C
Allowable temperature of normal concrete	28.5°C	28.5°C	28.5°C	28.5°C	28.5°C	28.5°C
Meet requirements?	Yes	Yes	Yes	Yes	Yes	Yes

Table 9   The upper and lower temperature difference results   of RCC at overwintering layer

Scheme	I		II		III	
Position	1352.5m	1355.5m	1352.5m	1355.5m	1352.5m	1355.5m
Highest average temperature of upper layer	18.1°C	18.8°C	18.4°C	19.3°C	20.2°C	21.0°C
Average temperature of lower layer	5.5°C	14.0°C	10°C	14.0°C	9.5°C	16.0°C
Upper and lower temperature difference	12.6°C	4.8°C	8.4°C	5.3°C	10.7°C	5.0°C
Allowable value	15°C	15°C	15°C	15°C	15°C	15°C
Meet requirements?	Yes	Yes	Yes	Yes	Yes	Yes

Table 10 The upper and lower temperature difference results   of normal concrete at overwintering layer

Scheme	I		II		III	
Position	1352.5m	1355.5m	1352.5m	1355.5m	1352.5m	1355.5m
Highest average temperature of upper layer	23.5°C	25.5°C	23.8°C	25.8°C	24.9°C	26.5°C
Average temperature of lower layer	5.5°C	19.0°C	9.5°C	19.0°C	9.0°C	20.0°C
Upper and lower temperature difference	18°C	6.5°C	14.3°C	6.8°C	15.9°C	6.5°C
Allowable value	16°C	16°C	16°C	16°C	16°C	16°C
Meet requirements?	No	Yes	Yes	Yes	Yes	Yes

The table 8 shows that the scheme I II and III can all meet the demands of concrete highest temperature. Compare the analysis of upper and lower temperature difference results in table 9 with that in table 10, it can be found that the upper and lower temperature differences in three different schemes can all meet the demands of control standards. But in scheme I, the upper and lower temperature difference of normal concrete at overwintering layer reaches 18°C which already exceeds allowable temperature difference standard. The reasons are as follows. Because of the low air temperature during overwintering intermittence period, the insulation measures have been taken at sides and top surfaces of concrete, however, average temperature of overwintering concrete is still low as cold lasts a long time when it return to construction next year. In addition, highest temperature of the new concrete after construction resume lead to the exceeding of upper and lower temperature difference because the hydration heat of normal concrete is high. In scheme II, the pre-heating treatment measure is taken on overwintering concrete. Then the average temperature of lower concrete is raised and the upper and lower temperature difference is reduced. In scheme III, the construction resume time is put off until mid-May when the temperature of old concrete rises at overwintering position, so it benefits reducing the upper and lower temperature difference. As a consequence, the upper and lower temperature differences of normal concrete and RCC concrete can all meet their allowable standards.

Table 11 Vertical tensile stress results at overwintering layer (Unit: MPa)

Scheme	I		II		III	
Position	1352.5m		1352.5m		1352.5m	
Concrete	RCC	Normal concrete	RCC	Normal concrete	RCC	Normal concrete
Max tensile stress	1.13	1.59	0.99	1.45	1.06	1.5
Time	the second winter					
Age of concrete	180d					
Allowable value	1.09	1.52	1.09	1.52	1.09	1.52
Meet requirements?	No	No	Yes	Yes	Yes	Yes

The Table 11 shows that in scheme I, the maximum tensile stress of RCC concrete at overwintering position is 1.13MPa and that of normal concrete is 1.71MPa, both of them exceed the maximum allowable vertical stress at overwintering joint position. In scheme II, the maximum tensile stress of RCC concrete at overwintering position is 0.99MPa and that of normal concrete is 1.45MPa, both of them can meet requirement of the maximum allowable vertical stress. In scheme III, the maximum tensile stress of RCC concrete at overwintering position is 1.06MPa and that of normal concrete is 1.50MPa, both of them can meet requirement of the maximum allowable vertical stress.

Table 12 The tensile stress results of new concrete after return to construction of Scheme II (Unit: MPa)

Scheme	II			
Position	1352.5~1355.5m		1355.5~1358.5m	
Concrete	RCC	Normal concrete	RCC	Normal concrete
Max tensile stress	1.36	1.76	1.44	1.91
Time	the second winter			
Age of concrete	180d			
Allowable value	1.66	2.09	1.66	2.34
Meet requirements?	Yes	Yes	Yes	Yes

The table 12 &13 shows that the maximum internal tensile stresses of new normal concrete are 1.91MPa and 2.03MPa after construction resume in scheme I and II. Those of new RCC concrete are 1.44MPa and 1.52MPa. The maximum tensile stresses all appear in cold of next (in 2012) winter, but they can all meet their allowable tensile stress standards.

Table 13 The tensile stress results of new concrete after return to construction of Scheme III (Unit: MPa)

Scheme	III			
Position	1352.5~1355.5m		1355.5~1358.5m	
Concrete	RCC	Normal concrete	RCC	Normal concrete
Max tensile stress	1.43	1.85	1.52	2.03
Time	the second winter			
Age of concrete	180d			
Allowable value	1.66	2.09	1.66	2.34
Meet requirements?	Yes	Yes	Yes	Yes

Through the crack prevention simulation of scheme Ⅰ, Ⅱ and Ⅲ, the scheme Ⅱ and Ⅲ are all feasible at overwintering position after construction resume from the perspective of highest temperature, upper and lower temperature difference, allowable vertical tensile stress and allowable tensile stress. The scheme Ⅲ of crack prevention measures at layer position is selected in this project because the preparation workload is heavy before construction resume after overwinter.

The effect of crack prevention measures at overwintering layer

According to the measured data of thermometers which are embedded below the overwintering insulating layer (elevation 1352.5m), minimum temperature at the boundary was 6.5°C and that in the middle of overwintering layer was 7.6°C during the overwinter from 2011 to 2012. The waterproof clothes with cornstalks, straws, polystyrene insulation (2.5cm thick) and polystyrene insulation (2.5cm thick) were gradually removed (the average time interval is 4 days) from April after overwinter. Large-area cracks were not founded after uncovering all the heat preservation covering when the top of overwintering concrete are checked. Only three short cracks were founded in dam segment of left bank slope. The preliminary reasons are as follows: because of the seepage at cofferdam and pit, the winter drainage canal was arranged at left bank slope next to dam segment slope. The large flow in drainage canal and low temperature of water lead to "Cold Shock Effect" in dam segment of left bank slope and then concrete cracked.

The sediment storage dam continue to pour concrete in mid-May 2012, the measures including pipe cooling, pouring temperature control and intermittence control were taken on the basis of commendatory crack prevention measures. Horizontal crack was not founded at overwintering position through the test of winter from 2012 to 2013. It is observed that the commendatory crack prevention measures of sediment storage dam at overwintering layer in Hohhot pumped storage power station are feasible.

Summary

This paper takes the sediment storage dam of the down reservoir of Hohhot pumped storage power station as a case, the heat preservation and crack control measures of overwintering area have been analyzed. The reasonable and feasible heat preservation measures have been determined by the simulation analysis on different heat preservation scheme from the inside and outside temperature difference and allowable tensile stress angle, and after winter severe cold test, this preservation measures work well. After overwintering period, the construction of the dam continues. In order to avoid the cracks in bonding zone between old and new concrete layers, the reasonable and feasible crack control measures have been determined by the simulation analysis on different crack prevention measures from the highest temperature, upper and lower temperature difference, vertical stress and allowable tensile stress angle. After winter severe cold test, cracks in bonding zone do not happen, and this crack control measures work well.

The overwintering problem about heat preservation and crack prevention in bonding zone should be given particular attention. The implementation of heat preservation and crack control measures of overwintering layer concrete of the sediment storage dam of the down reservoir of Hohhot pumped storage power station works well, which can provide a reference for the similar problems in other engineering.

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