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Application of Geomembrane in Large Pumped Storage Power Projects

Shi Hanxin, Li Jianjun*

POWERCHINA, Zhongnan Engineering Corporation Limited, Changsha, China

Email address

11359481@qq.com (Li Jianjun)

*Corresponding author

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Abstract: The geological condition of the upper reservoir for the said pumped storagepowerproject is complex, which has the outstanding problems in the reservoir bottom seepage. In order to solve the questions of reservoir formation and seepage, the overall anti-seepage scheme is used in the reservoir basin. Due to the great variation in thickness of the fill at the bottom of the reservoir as well as large and in-homogeneous settlement deformation of the back-filling, HDPE geomembrane is selected as the material for building the reservoir bottom seepage control system because it has strong adaptability to uneven deformation, which solves the reservoir seepage problem completely. The reservoir seepage is extremely low when completed, meanwhile, the anti-seepage scheme contributes a lot to reduce the construction difficulty, speed up the construction schedule and save the project investment. Design and application of geomembrane seepage control system are mainly introduced in this article, including selection and design of the material for the seepage control layer, design of peripheral connection of the geomembrane, and the geomembrane construction technology etc.

Keywords: Geomembrane, Seepage Prevention of Reservoir Bottom, Pumped Storage Power Project, Reservoir Seepage

1. Introduction

The said Pumped Storage Power Plant, is a project classified as Grade Large 1 of Class I with an installed capacity of 1500 MW (6×250MW). The project plant has a maximum water head of 290 m, a minimum water head of 227.7 m and a rated water head of 259.0 m. The project structures are mainly composed of the upper reservoir, the water conveyance system, the power house and the lower reservoir.

The upper reservoir is formed with the mountain ridges on the north, west and south as the shoreline and by building a dam in two gentle gullies on the east side, where excavation is carried out with consideration of the balance of excavation and filling. The upper reservoir has a normal water storage level of the 291.00 m, a dead water level of 254.00 m and a storage capacity of 11.95 million m^3.

Generally, the watershed area in the perimeter of the reservoir is simple and thin (especially on the southern and northern shore), where faults and joint fractures are densely developed in the rock, forming a well permeable network. The water table in the perimeter of the reservoir and the roof of the aquiclude, lying deeply, are both lower than the normal water storage level of the reservoir. After the reservoir is impounded, the reservoir water will leak out of the reservoir through the watershed. In addition, due to the development of small faults, it's apt to form concentrated channels for reservoir water seepage, and seepage deformation might appear along them. Furthermore, because of the small rain catchment area and small amount of natural water inflow, the storage power project has high requirements for seepage control of the upper reservoir. Therefore, seepage control needs to be well done for the whole upper reservoir basin.

Because the fill at the bottom of the upper reservoir varies greatly in thickness, from 1.5 m to 75 m and the uneven settlement deformation will be large accordingly. The seepage control material should have the ability to adapt to the uneven deformation. Therefore, it is recommended to adopt flexible material for seepage control. Design and construction quality of the upper reservoir bottom seepage control system is one of the key factors to ensure safe operation of the project.

On the basis of the collected data of some similar projects and related experiences at home and abroad, according to the topography and engineering geological conditions of the upper reservoir, with comprehensive consideration of such aspects as minimizing the dead storage capacity of the upper reservoir and the large amount of waste ballast dump, shortening the initial impoundingtime of the reservoir, and reducing the difficulties of construction, operation and maintenance, reducing operation and maintenance costs and minimizing project investment, etc., the design engineers have studied and compared several alternatives, conducted theoretical analysis and scientific experiments for the reservoir bank and bottom seepage control system in the preliminary design stage. After techno-economic comparison, it is finally recommended to take the proposal of control seepage with concrete face for the reservoir bank and the dam body, and geomembrane on the backfill rock ballast for the reservoir bottom.

Geomembrane is a flexible waterproof material with good impermeability, heat resistance, cold resistance, chemical stability, high tensile strength and elongation at break, strong ability to adapt to uneven settlement, and low cost. It has been widely used in reservoir seepage control works, such as seepage control and rehabilitation of Shibianyu Reservoir, and anti-seepage control of the reservoir bottom of Tai'an Pumped Storage Power Station. The geomembrane seepage control adopted for the upper reservoir bottom of the said project is in line with the actual conditions.

As the seepage control body for the reservoir bottom, the geomembrane is connected with the bank and the dam embankment respectively with the drainage gallery and the concrete face boards, forming a complete seepage control system. Dam site of the power station's upper reservoir is irregular in terrain, where the geological structure of the bed rock is complex, and there are various materials used for the dam embankment (some of them is strongly weathered material from the excavation of the upper reservoir); the reservoir bottom is backfill with ballast with local height exceeding 70m, which causes to prominent uneven deformation. Therefore, in the bidding design stage, structural safety analysis has been carried out for the upper reservoir and the dam, including the reservoir bottom fill area, consisting of dam slope stability calculation, dam section optimization analysis, 3D FEM calculation and analysis, geomembrane deformation characteristics analysis, etc., providing basis for dam structure optimization and geomembrane material selection. In the detailed design stage, based on the relevant laboratory experiment of dam body fill materials, 3D FEM static and dynamic calculation and analysis of the dam has been conducted, for the optimized scheme of the dam body and the reservoir bottom, which shows that the seepage control system designed for this project is safe. The current standards and codes have regulated construction of the seepage control layers, hydraulic calculation and stability of the geomembrane in details. According to the features of the project and requirements of these standards and regulations, the performance indexes, deformation control measures and detailed connection structure design of the seepage control geomembrane which adapt to the requirements of deformation arising from deep and thick fill ballast are proposed.

2. Method

The anti-seepage area at the bottom of the upper reservoir is about 250,000 m^2, including 1/3 of excavation area and 2/3 of fill area. Due to the different thickness of the reservoir fill, according to the results of the static and dynamic 3D FEM calculation and analysis, the maximum settlement in the fill area of the reservoir is 125 cm at completion of geomembrane placement, and 170.4 cm in the full storage period. The uneven settlement at the bottom of the reservoir is comparatively large. Therefore, the seepage control body of the reservoir bottom needs to meet the requirements for adapting to the uneven deformation of the foundation, coordinating with the deformation of the connecting plate of the concrete faced rock-fill dam, and have high seepage control performance etc.

The geomembrane is used as the single anti-seepage layer at the bottom of the whole reservoir. The anti-seepage body has a top elevation varying between 239.80 m and 247.80 m, a maximum/minimum working water head of 51.84 m/6.2 m, and a maximum daily working head variation of 37 m. The reservoir bottom is formed based a principle of "high-cutting and low-filling" – excavating the site part above the elevation of 245.80 m into a platform which is 245.80 m high and filling the site part below that with ballast to an elevation of 245.80 m. At the boundary between the cut area and the fill area, a horizontally 10 m-wide belt area with a slope of 1:5 is over-cut and then backfill to form a transition zone.

The construction layers of the seepage control system on the surface of the bottom cut platform area and the fill area of the upper reservoir are, from top to bottom, 0.1 m thick protective face with concrete precast blocks, non-woven filament geotextile (500 g/m^2), 1.50 mm thick HDPE geomembrane, 3D composite drainage network (1300 g/m^2), 5 cm thick sand cushion, 0.4 m thick gravel underlayer and 1.5 m thick transition layer, under which is the cut bedrock surface or the top surface of the fill.

2.1. Selection and Type of Seepage Control Material at the Bottom of the Reservoir

The project has a large area of the reservoir bottom for seepage control, where the geomembrane is subjected to a high water head. Referring to the application experiences of geotechnical composite materials such as channel seepage control, coastal protection, embankment dam etc. at home and abroad, the joints should be minimized. According to information from the manufacturers, the production width of polyethylene (PE) geomembrane is up to 8.0 m. As a new type of synthetic geotechnical waterproofing material that emerged in the 1980s with excellent performance indicators, it has strong weldability, anti-aging ability, chemical resistance, environmental stress cracking resistance and anti-puncture ability, and the placement construction workmanship is simple. Through investigation and analysis of the technical performance of products provided by some domestic and foreign manufacturers, and plus with experiments and demonstrations, the technical indicators of high-density polyethylene (HDPE) geomembrane are better than ordinary PE film and PVC film, and HDPE geomembrane is selected.

The composite geomembrane, as the anti-seepage body of the reservoir basin, is provided at the bottom of the reservoir to change the structure of the fill area of the basin. The original relatively tightly combined earth and stone materials are separated by a soft and flat composite geomembrane. They can only be indirectly connected together by a composite geomembrane. Only when the composite geomembrane is subjected to tensile deformation with the bottom back filler, can it have a certain restraining effect on the deformation of the earth and stone, and the greater the tensile strength, the greater the restraining effect on the deformation of the earth and stone.

In FEM calculation, the composite geomembrane embedded in the reservoir basin is set as a set of flexible planar units along the bottom plane of the basin that can neither withstand the bending moment nor the pressure. According to the tensile test curve of the composite geomembrane, the tensile strain in the meridional direction is between 0 and 50%, and the tensile force and strain are close to the linear elastic relationship; the tensile strain in the zonal direction is between 0 and 80%, and the tensile force and strain are close to the linear elastic relationship. The strain of the composite geomembrane in the basin is generally less than 20% under actual working conditions. The stress-strain relationship is considered as the linear elastic mode in the calculation. Different elastic constants are taken for the meridional and zonal directions with consideration of different properties of the composite geomembrane in the directions.

According to the results of 3D FEM static and dynamic calculation and analysis, the tensile force withstood by the geomembrane of this project in meridional/zonal directions is 1.23 (kN/m)/1.23 (kN/m) at completion of geomembrane placement, and 6.18 (kN/m) / 9.28 (kN/m) in full water storage period, so the high density polyethylene (HDPE) geomembrane is selected to satisfy the tensile strength. After investigation of the performance indexes of geomembrane materials provided by many major manufacturers in China, and with consideration of the requirements of the specifications, it is proposed that the physical and mechanical parameters of the geomembrane used in this project should not be lower than the required values in Table 1.

2.2. Geomembrane Thickness Determination

The thickness of geomembrane directly affects the quality of the project. With consideration of such purposes as minimizing seepage, avoiding construction damage, prevention of water pressure breakdown, foundation deformation, geomembrane tearing, etc., the geomembrane must be enough thick.

Table 1. *Physical and mechanical indexes of HDPE geotechnical membrane.*

Items		Unit	No.
Density		g/cm^3	0.9525
Water absorption rate		%	0.02
Carbon black content		%	2.4
Melt flow rate		g/10min	0.13
Tensile yield strength	Transversal	MPa	19.1
	Longitudinal	MPa	19.2
Tensile yield elongation	Transversal	%	16
	Longitudinal	%	16
Tensile breaking strength	Transversal	MPa	31.5
	Longitudinal	MPa	32.1
Tensile elongation at break	Transversal	%	772
	Longitudinal	%	764
Tear strength along the angle	Transversal	N/mm	146
	Longitudinal	N/mm	145
Dimensional stability (100°C, 15 min)	Transversal	%	-0.45
	Longitudinal	%	-0.33
Puncture resistance		N	648
Oxidation induction time at 200°C		min	>135
low temperature embrittlement impact performance at -70°C		—	pass
Water vapor permeability coefficient		g/m·s·Pa	4.86×10^{-13}
Resistance to environmental stress cracking		—	2000h No damage

The thickness of the geomembrane is related to the particle size of the underlying cushion and the water head that is subjected to it. The related test results show that the smaller the particle size of the cushion is and the better the gradation is, the higher ability to withstand water pressure the geomembrane has. The calculation of geomembrane thickness is based on the calculation formula in the "Synthetic Materials Engineering Application Manual" [1], which is the calculation formula in "The Earth Dam Design" published by the former Soviet Union in 1987:

$$t = 0.135E^{1/2}\frac{Pd}{[\sigma]^{3/2}} \quad (1)$$

Where E is the modulus of elasticity of the film at the design temperature, 120 MPa; P is the water pressure of the film, 0.518 MPa; $[\sigma]$ is the allowable tensile stress of the film, 3 MPa; d is the maximum particle size of the earth and/or sand pebbles contacted with the film, 4 mm; t is the film thickness in mm (if $t<\frac{1}{3}d$, $\frac{1}{3}d$ will be used).

The maximum working head of the upper reservoir bottom of the project is 51.84 m, and the thickness of the geomembrane calculated is 0.665 mm, which is less than $\frac{1}{3}d$ =1.333 mm. According to SL/T231-98 "Technical Specifications for Polyethylene (PE) Geomembrane Anti-seepage Engineering" [2], PE geomembrane thickness can be calculated according to the theoretical formula, or the thickness can be determined by the test method. In addition, application conditions such as exposure, burial pressure, climate and service life etc. should also be considered. However, in application of geomembrane, there are always sharp corners in the underlying layer. In addition, according to various test results, the thicker the film is, the slower it is to age. Such factors should also be considered in determination of the film thickness. Sufficient safety margin should be considered in selection.

The calculated film thickness is 1.33 mm. With reference to the experience of similar projects at home and abroad, the HDPE film with a thickness of 1.5 mm was finally selected.

2.3. Construction Design of Geomembrane Seepage Control Layer

The geomembrane seepage control facility is composed of a lower support layer, a geomembrane seepage control layer and an upper protective layer.

2.3.1. Lower Support Layer

The lower support layer of the geomembrane seepage control body should have the following functions: Firstly, It has certain bearing capacity for transferring the load during construction period and operation period; Secondly, It has suitable particle size, geometry and gradation, where its maximum particle size should be limited to avoid the geomembrane being broken under the action of high water head; Thirdly, to ensure the smooth drainage under the geomembrane; Fourthly, the grain size of the filling material between the compacted ballast at the bottom and the geomembrane should be gradually transitioned to meet the inter-layer filtration so as to ensure stable penetration.

According to SL/T231-98 "Technical Specifications for Polyethylene (PE) Geomembrane Seepage Prevention Engineering", the geomembrane should be placed on a solid foundation and the level should be flat. The surface in contact with the membrane should be a compacted fine soil layer, a fine sand layer or a concrete layer, and the layer should be flat.

With consideration of the above factors, the lower support layer of the geomembrane from top to bottom includes: 1300 g/m^2 three-dimensional composite drainage network, 5 cm thick sand cushion, 40 cm graded gravel cushion, and 150 cm thick transition layer.

2.3.2. Geomembrane Anti-seepage Layer

The seepage control requirements of this project are relatively high, and the thickness of geomembrane used is relatively large. If a composite geomembrane is selected, after the film is thermally composited, there will be severe wrinkles on the reserved under compounding joints on both sides, which will affect the welding quality of geomembrane joint. On the other hand, the quality of the film in the composite geomembrane is not as good as that of the single film, and there are more surface defects than those on the single film. Therefore, a smooth HDPE film with a thickness of 1.5 mm is selected as the geomembrane seepage control layer. The width of the geomembrane should be selected to minimize the number of joints in construction, larger width should be used as much as possible. According to the production capacity of the manufacturers investigated, the geomembrane width of 8 m is selected.

2.3.3. Upper Protective Layer

In order to prevent the surface of the geomembrane from ultraviolet radiation, high or low temperature damage, biological damage and mechanical damage, a protective layer should be provided on the geomembrane. The protective layer is selected as 500 g/m^2 geotextile, and should be overlaid with precast blocks for being kept in place after being placed.

2.3.4. Calculation of Seepageof Geomembrane Seepage Control Layer

The seepage of the geomembrane anti-seepage layer consists of two parts: the seepage through infiltration of the geomembrane and the seepage through the geomembrane defects formed in the construction.

According to the engineering analogy method, the permeability coefficient k of the geomembrane is determined to be 10^{-12} cm/s. The Darcy's equation is used to calculate the water seepage generated by the geomembrane itself in each operating condition. The calculation formula is

$$Q=kAH/L=kAJ \quad (2)$$

Where k is the permeability coefficient of the geomembrane; A is the percolation cross-sectional area; J is the seepage slope; H is the seepage head; L is the flow path along H.

Assume that the geomembrane has a defect each 4000 m^2, which has an equivalent diameter of 3 mm, and calculate the seepage through the geomembrane defects formed in construction based on orifice outflow, with the calculation formula:

$$Q=\mu An(2\times 9.81H)^{0.5} \quad (3)$$

Where μ is the flow coefficient; A is the single defect area; n is the number of defects; H is the seepage head. The calculation results are shown in Table 2.

It can be seen from the calculation results in Table 2 that the seepage through the geomembrane is about 70.08 m^3/d, and the seepage through construction defects is 742.12 m^3/d. The total seepage of geomembrane is 812.2 m^3/d, which accounts for 0.58 over ten thousands of the total storage capacity, and the seepage is small enough to meet the engineering requirements.

Table 2. *Seepage quantity of impervious layer of geomembrane.*

Calculation condition	Seepage water head$H$/m	seepage through the geomembrane	seepage through construction defects	Total seepage
		$Q_1/(m^3 \cdot d^{-1})$	$Q_2/(m^3 \cdot d^{-1})$	$Q/(m^3 \cdot d^{-1})$
Normal water level	291.00	69.22	737.53	806.75
Design flood level	291.44	69.81	740.69	810.50
Check flood level	291.64	70.08	742.12	812.20

2.4. Joint Design of Geomembrane Seepage Control Facility

2.4.1. Joints and Slack

The joint design of the geomembrane should be such that the joints has a minimized number and is parallel to the direction of the higher tensile stress; the joint is placed on a flat location to avoid bending. The HDPE film joints should be made with a sweat soldering process with a welding overlap width of about 12 cm. The tensile strength of the welded joints should not be lower than the strength of the base metal.

In order to coordinate the deformation of the seepage control geomembrane and that of its connection locations with the ballast under it, panel and bank slope, a certain slack should be reserved on the flat part, and fold allowance should be reserved at the turning locations. The geomembrane should be placed loosely to release stress and avoid the loss of strength, thinning or cracking due to creep or fatigue of polymer by reason of long-term stress or repeated stress.

2.4.2. Design of Connection of Geomembranewith Face Connecting Plate and Bottom Observation Gallery

The geomembrane is connected with the face connecting plate and the bottom observation gallery with anchorage, as shown in Figure 1. The 1.5 mm thick geomembrane is inserted into the anchoring groove and mechanically connected with the bolt. The contact area between the geomembrane and the anchoring groove is coated with SR primer and SR leveling layer, and M7.5 mortar is backfill in the groove after the geomembrane is fixed, and a geomembrane with a width of 600 mm and a thickness of 1.5 mm is placed on the top of the anchoring groove. The two sides are respectively inserted into the geomembrane of 100 mm in the lower part, and finally the protective geotextile (500 g/mm^2) is covered, forming a complete closed system.

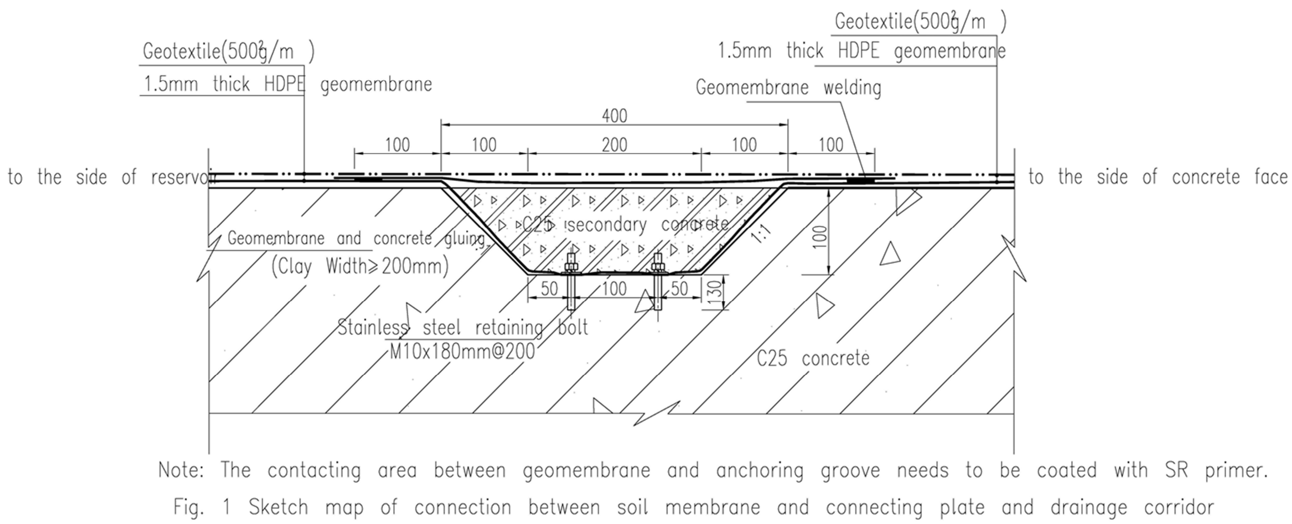

Figure 1. *Connection Design of Geomembrane at the Anchoring Trench.*

2.4.3. Design of Connection of Geomembranewith Inlet (Outlet) of Upper Reservoir

The geomembrane and the inlet (outlet) of the upper reservoir are mechanically connected by bolts. The construction sequence from top to bottom is: 2 times SR primer with the width of 200 mm, SR leveling layer with the width of 200 mm and thickness of 5 mm, 2 times SR primer with the width of 200 mm, 1.5 mm thick smooth HPDE geomembrane, and 2 times SR primer with the width of 200 mm. After the geomembrane is fixed with bolts, the surface is compacted with C25 second-stage concrete. The 3D composite drainage net (1300 g/m^2) and geotextile (500 g/m^2) are both inserted into the second-stage concrete with a length not less than 200 mm, forming a complete closed system; as shown in Figure 2.

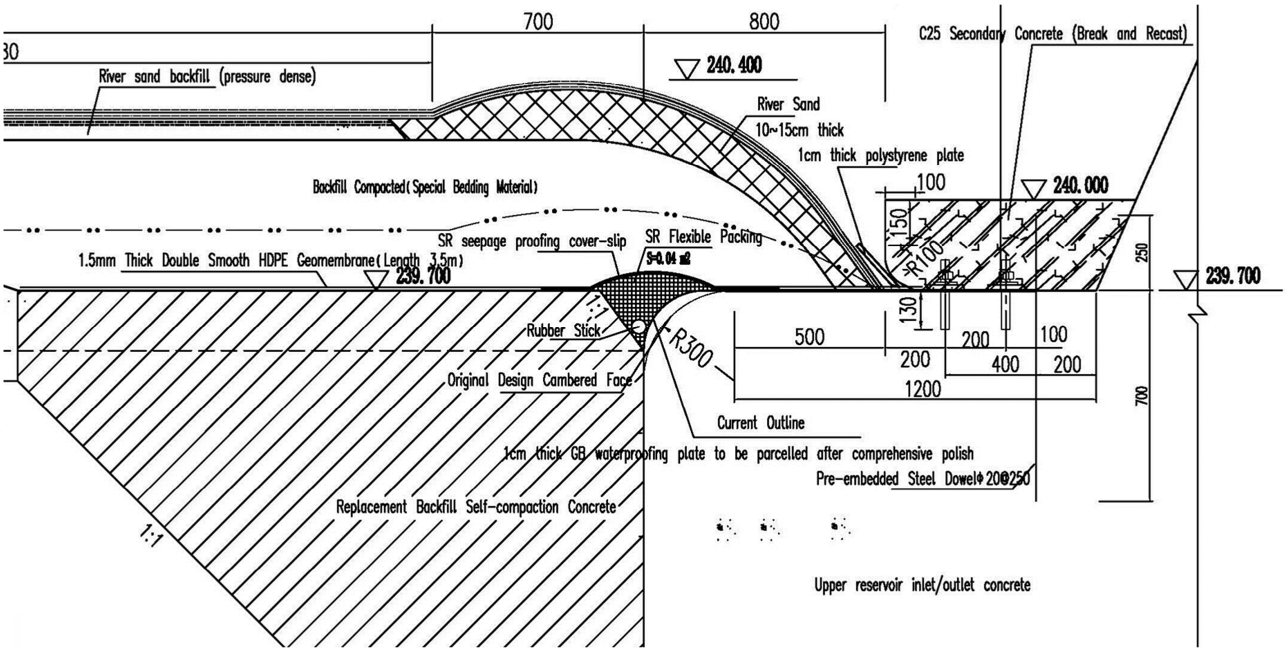

Figure 2. *Sketch map of connection of geotechnical membrane and inlets (outlets) of upper reservoir.*

2.5. Deformation Control Design of Geomembrane

The seepage control HDPE geomembrane is mainly horizontally placed on the surface of the upper reservoir bottom. The deformation control factor is mainly determined by the afforded water head, the deformation of the sub-filled gravel area and the deformation adaptability of the geomembrane itself. In the view of water head, the maximum working water head is about 51 m. Because of actual requirement of the power station operation, it is impossible to control the geomembrane deformation by reducing the water head, but only by improving the geomembrane material performance indexes to adapt to the deformation and reducing the future settlement deformation in the lower fill ballast body. The former can be achieved by the manufacturer to improve the raw material composition proportion, introduce advanced production equipment, and strengthen production process control. For the latter, the control measures are detailed as below.

For the fill ballast at the reservoir bottom, as the quality of the fill materials used is poor, in the actual construction, 25 t self-propelled vibro roller is used for compaction by layers (the compaction layer is controlled by 80 cm, with 8 times of compaction, and 8% water sprinkling) to ensure that the dry density and porosity after compaction meet the design requirements, and that the settlement deformation in the later stage is as small and even as possible. At the same time, after completion of the fill ballast compaction, a settlement period of more than 3 months should be reserved before commencement of the surface geomembrane placement. In addition, in the peripheral area of the inlet and outlet tower bases of the upper reservoir, the cushion and transition material in the range of 5 m deep and 10 m wide below the surface layer are filled and compacted by cement mixture and reinforced geogrid to ensure that the settlement deformation of the fill in the circumferential area of the shaft is as small as possible, so as to meet the requirements of geomembrane deformation control, and to prevent the geomembrane from being damaged due to excessive deformation of the bottom at the joint with the shaft.

In addition, in order to reduce the adverse impact of uneven settlement in the fill area of the upper reservoir on the geomembrane seepage control system, according to the settlement isoline distribution map of the reservoir bottom in the storage period as the result of the FEM calculation, excessive fill height is considered as the settlement margin for the fill area of the reservoir: by taking the excavation and fill boundary as the starting point, the bottom fill area with gallery in the west of the reservoir is transited with a 1% pre-filled gentle slope, and the bottom fill area with connecting plate to the main dam on the east is filled with a 5% pre-filled gentle slope, where the maximum excessive fill thickness is 70 cm. In this way, the placement length of the geomembrane is appropriately increased, the excessive tensile deformation of the geomembrane due to settlement in the water storage period is avoided, and the settlement deformation and stress conditions of the reservoir bottom are improved, and the damage of the bottom seepage control body due to uneven settlement is avoided, achieving the expected results.

3. Conclusions

1) The pumped-storage power station has high requirements for seepage control of the upper reservoir. Due to poor geological conditions and few natural run off, a seepage control system is established for the entire reservoir. The bottom of the reservoir is placed with geomembrane.

According to the calculation and analysis, the uneven settlement deformation of the reservoir bottom is large, and the geomembrane is a flexible seepage control material and can be adapted to this situation. The geomembrane serves at a high working water head and is first used for a forebay area around the inlet and outlet. After the water storage operation for more than 3 years, the anti-seepage effect is good, and the measured seepage is stable within 5L/s, which is far less than the standard requirements, which is 0.02~0.05% of the reservoir water capacity.

2) The main difficulties of geomembrane anti-seepage are to control the deformation and the construction quality of geomembrane joints. Taking reasonable measures according to the construction process requirements to ensure the construction quality is the key to meet the anti-seepage requirements and safe operation of the reservoir.

3) Through rational design, careful construction, and continuous improvements of manufactures in the products and processes, with actual proven success in operations of more projects, the geomembrane will have a broader application prospect in hydropower and water conservancy projects.

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