Reconstruction and Reinforcement New Techniques for Masonry Gravity Dams Upstream Anti-seepage Panels

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Abstract. Masonry gravity dam type has been used widely in developing countries, in which China also has built many masonry gravity dams in the past. Most of the masonry gravity dams have the structure of internal masonry and external reinforced concrete. Due to much internal masonry void, the dam upstream anti-seepage panel becomes the key part of its dam body anti-seepage system. After a long-time running, many masonry gravity dams’ upstream concrete panels have appeared many deficiencies such as aging, cracking, exposing steel bars and separating calcium, which have generated serious leakage problems, and then threatened the safety of the dams’ body and residents downstream, consequently the upstream anti-seepage panels should be restructured and reinforced with new techniques. This article summarizes technical difficulties and methods of masonry gravity dams’ upstream anti-seepage panels reconstruction and reinforcement, it also combined with an engineering project to introduce the new techniques and its effect of the upstream anti-seepage panel reconstruction and reinforcement.

1. Introduction
Masonry gravity dam type has many advantages, such as rich source of building material, low construction cost, dam crest can overflow, temporary water can flow through dam body during construction and simple construction techniques, the dams of this type have been developed rapidly in developing countries.

In ancient China a number of gate-dams which are similar to masonry gravity dams have been built, they could play a role in water retaining and flood discharge, the dams body material used at that time was mainly artificial hewn stone, the bonding materials between the stones were mainly a kind of composite with glutinous rice and lime mortar; in the period from the liberation to the reform and opening up, our country has attempted to use modern engineering techniques and built a large number of masonry gravity dams, the structure of which has been generally ‘gold package silver’ structural model with internal masonry and external reinforced concrete pouring package. A lot of void has commonly exist in these dams’ masonry, that caused the dams can not effectively play the role of anti-seepage, and then the upstream reinforced concrete panels have become the mainly role of anti-seepage. Because the material performance and technical level is limited in the past, and after long time running by now, many masonry gravity dams upstream panels have gradually generated much crack, and then different degrees leakage of the dams body has appeared. These diseases and defects endanger the dams themselves and the resident downstream. Therefore, it is needed to research and use new techniques to reconstruct and reinforce for masonry gravity dams upstream anti-seepage panels.
2. China masonry gravity dams construction and reinforcement situation
At present, China has built a largest number of masonry gravity dams in the world, the number of masonry gravity dams above height of 15m has exceeded more than 2,000, in which the high dams above height of 70m reached the number of 10, mostly masonry gravity dams have been built before the reform and opening up, the majority of masonry gravity dams have been running for more than 40 years, the dams body have gradually emerge a variety of defects and dangers, especially the problems of leakage have become more serious. In strong support of the national government, local water departments have organized necessary reinforcement projects for the dams which has been identified as dangerous dams.

The National Science and Technology Support Program of Ministry of Science and Technology established the key project as ‘dams security key technology research’, in order to study reinforcement technology principle for dangerous reservoirs. The extensive collection and disposal of research projects across the country, the number of the projects has reached more than 2311, the datas and cases have been collected from 14 provinces (or autonomous regions, municipalities) throughout the country, involved all scales and various types of dams[1]. The investment statistics of several reinforced masonry gravity dams extracted from the collected cases are shown in Table 1, the total investment of dams reinforcement include two parts of anti-seepage reinforcement and structural reinforcement in this table.

Table 1. Investment Statistics of several masonry gravity dams reinforcement
(Investment Unit:million yuan)

| Item                      | Large-scale | Medium | Small-scale |
|---------------------------|-------------|--------|-------------|
|                           | Total       | Average| Total       | Average | Total       | Average |
|                           | investment  |         | investment  |         | investment  |         |
|                           | Quantity    |         | Quantiy     |         | Quanty      |         |
| Dam reinforcement         | 3593        | 1       | 3593        | 7285    | 10          | 729     | 2270        | 12      | 189        |
| Anti-seepage reinforcement| 2501        | 1       | 2501        | 3998    | 10          | 400     | 1251        | 12      | 104        |
| Structural reinforcement  | 1092        | 1       | 1092        | 3287    | 10          | 329     | 1019        | 2       | 85         |

From the table above,total investment of masonry gravity dams anti-seepage reinforcement is 1.4 times as much as structural reinforcement, total investment of anti-seepage reinforcement is 59% of total investment of dams reinforcement, therefore, the percentage of the investment of masonry gravity dams anti-seepage reinforcement is relatively higher, and reinforcement technology is more complex.

There are three main forms of anti-seepage facility layout of masonry gravity dams in our country: the first one is setting concrete or reinforced concrete anti-seepage panels on the dam upstream face, the second one is setting a concrete anti-seepage core wall in the dam body’s upstream side, the third one is making dam body itself anti-seepage. Most high masonry gravity dams adopt the first forms of setting anti-seepage panels on the dam upstream face,such as Zhuzhuang Reservoir in Hebei province, Baoquan Reservoir and Qingtianhe Reservoir in Henan province, Yudong Reservoir in Yunnan province, Jiaokou Reservoir in Zhejiang province, which all adopt the first dams anti-seepage layout form[2].

3. Difficulties and methods of anti-seepage panels reconstruction and reinforcement

3.1 Main reinforcement difficulties
Masonry gravity dams anti-seepage reinforcement measures mainly include reconstructing panels or repairing the original reinforced concrete panels, in which the reconstructing panels measure need to add additional reinforced concrete panels upstream on the outside of original panels, or reconstruct new anti-seepage panels after dismantling the original upstream panels.Adding reinforced concrete panels on the outside of the original upstream panels can retain the original panels, that also retain part of anti-seepage performance of the original panels, that can enhance the capacity of a dam anti-
seepage, that won’t damage the masonry dam body, and there is less difficulty of construction, therefore, the measure of adding upstream anti-seepage panels has usually been taken to reinforce masonry dams, however, reconstruction and reinforcement of anti-seepage panels exist following several aspects of technical difficulties and problems.

- Stability of reconstructed panels structure. Concrete or reinforced concrete structure styles have been generally adopted to reconstruct the panels, which density is high. It is needed to take measures to bear the weight of the panels, and tightly integrate the new panels with the original dam structure, which can make sure to avoid new panels disengagement from the old panels, and ensure the panels structure itself absolutely stable, that is the prerequisite to play the role of anti-seepage of the panels.

- Parting and sealing of reconstructed panels. The upstream anti-seepage panels are the most important anti-seepage barrier, their parting and sealing place is their weakest part of anti-seepage, the panels’ parting and sealing failure is usually the main reason of seepage destruction of dams body. Anti-seepage panels’ reconstruction need to be combined with the original structure, scientific and rational design to set parting and sealing, and apply reliable sealing structure.

- Anti-crack of reconstructed panels. The area of a masonry dam upstream is generally large, the deformation and temperature changes of the dam body will directly affect the stress and stain of the reconstructed panels, concrete alkali activity will lead to the gradual expansion of the panels’ internal structure, which are likely to cause reconstructed panels’ cracking damage, such problems have arisen in masonry dam reinforcement projects which have been completed in our country, in order to solve these problems, it is needed to set parting properly, improve material performance and enhance panels strength to satisfy the anti-crack requirements.

- Concrete impermeability and anti-freezing and anti-corrosion of reconstructed panels. Because there are some environmental adverse effects, the panels concrete is required to have higher performance. During the period of large reservoir mansony dam operation with upstream filling water, the bottom of anti-seepage panels have to bear high waterhead by long-term, the panels concrete should have sufficient capacity of impermeability. In severe cold region, due to circulation of freezing and thawing in winter, the using durability will be adversely affected, therefore panels’ concrete should have certain performance of anti-freezing. Environmental water has a corrosive effect on panels’ concrete in varying degrees, the codes of our country have specify corrosive performance of environmental water into three categories including the general acidic type, carbonated type, bicarbonate type, magnesium ions type and sulphate type, when the water corrosive level has been identified as above or including mildly corrosive level, it is needed to offer special requirements for the concrete material.

3.2 Main reinforcement techniques

On account of the main reinforcement difficulties of masonry gravity dams upstream anti-seepage panels, the following appropriate reinforcement methods and techniques can be taken for the panels reconstruction.

- In order to ensure the structural stability of reconstructed anti-seepage concrete, three methods can be taken to provide sufficient vertical holding force and horizontal tensile force for the panels. The first method is setting up post-anchoring chemically bonded rebars between the old and new panels, which take advantage of the shear and tensile strength of the rebars to provide vertical holding force upward and horizontal anchoring force. The second method is brushing inorganic interface glue at the old and new concrete panels interface, it can strengthen the stick force between the old and new concrete panels, which take advantage of interface stick to provide vertical holding force and stick force for the reconstructed panels. The third method is locating the reconstructed panels bottom on bedrock or concrete slab, which can provide reverse vertical holding force.

- In order to coordinate the deformation of reconstructed panels and the original panels, and ensure panels sealing reliability, the vertical parting of reconstructed panels should be cut through the vertical parting of original dams body, horizontal parting can be set up as required, reliable sealing
structure should be adopted in parting place, it can be considered to repair and strengthen the original panels’ sealing structure, or reconstruct sealing system in reconstructed panels.

- In order to prevent the panels from crack deformation, there are three solutions such as that enough structural expansion joints should be set up for the panels deformation, or strengthen their own strength or improve construction process. It is necessary to properly design the size between the partings and design the width of every partings. Panels surface layer should be properly fixed with anti-crack rebars to resist temperature stress due to frequently temperature changes outside. Necessary temperature control methods should be taken in the concrete pouring process, and it is necessary to intensify the early concrete curing.

- In order to ensure reconstructed panels have enough anti-seepage, anti-freezing and anti-corrosion performance, it is needed to select appropriate strengthen concrete according to the environmental category of the dams, control the maximum chloride content of the concrete, avoid directly using of the concrete with alkali activity, enhance the concrete compactness, consider to use fiber reinforced concrete, and add additives properly when it is necessary, using anti-corrosion concrete cement in chemical corrosive environment, or using a special surface protective coating, and so on. Reconstruction and reinforcement new techniques for masonry gravity dams upstream anti-seepage panels will be exactly introduced below through an instance of a certain reservoir reinforcement project in China’s Jiangxi province.

4. Anti-Seepage panel reconstruction and reinforcement Project instance

4.1 Reinforcement project overview

4.1.1 Project profile

The certain reservoir in China’s Jiangxi province has whole storage capability of 118 million cubic meters, it is a large-scale reservoir with comprehensive utilization such as flood control, irrigation, water supply and electricity generation. The reservoir’s water-control project includes a main dam and auxiliary dam, emptying bottom tunnel and water diversion tunnel.

The main dam is a masonry gravity dam with concrete anti-seepage panels, the dam crest elevation is 215.2m, its width is 8.0m, its maximum height is 43.4m, the dam crest length is 357m (Y0+050.0~Y0+407.0), in which the overflow dam section length is 81m (Y0+102.5~Y0+183.5), the overflow dam is composed of five sluice chambers, every sluice chamber width is 12m, they are controlled by top emersed arc steel gate, the overflow weir crest elevation is 204m. The main dam upstream elevational view is shown in Figure 1.

![Figure 1. The masonry gravity dam upstream elevational view](image-url)
4.1.2 Panels leakage situation
After years of operation, the masonry gravity dam’s upstream concrete panels had appeared many deficiencies such as cracking, exposing steel bars, cellular holes and separating calcium, many obvious cracks and leakage had generated in the dam body’s corridor, part of the leakage water was rusty water, long-term seepage and separating calcium led to form many stalactites (Figure 2), so the panels’ concrete anti-seepage grade did not satisfy the security requirements, there were a lot of weaknesses in the anti-seepage system, and the danger of leakage had happened during the dam running, therefore the seepage performance of the masonry gravity dam was insecure.

![Figure 2. Leakage and separating calcium in the dam body’s corridor](image)

4.1.3 Anti-seepage reinforcement measures of the dam
To solve the problems of dam leakage, the main anti-seepage reinforcement measures for the dam is reconstructing anti-seepage panels on the original anti-seepage panels, reconstructed panels have reinforced concrete structure, and the concrete grade is C25. The anti-seepage panels have a outline of polyline, the break point elevation of which is 188.00m, above 188.00m the panels’ outline is vertical, the thickness is 1.0m, under elevation of 188.00m the panels’ outline is a slope with a ratio of 1:0.25, and the thickness is 1.46m. Panels’ top elevation of the overflow dam section is same as the top elevation of the upstream dam face, and the panels smoothly connect the spillway surface structure, panels’ top elevation of the non-overflow dam section is same as the dam crest elevation, which elevation is 215.20m. The thickness in the place of the dam toe is 2.7 percent of its maximum waterhead, the ratio is in experiential range of 1/30 to 1/60[3]. The cross-section of the overflow dam section of the masonry gravity dam before and after anti-seepage reinforcement is shown in Figure 3.

![Figure 3. The overflow dam section’s cross-sectional view before and after reinforcement](image)
The concrete anti-seepage panels have been located on the bedrock of the dam upstream, the reconstructed anti-seepage panels are anchored with the upstream anti-seepage panels of the original dam through bonded rebars, the original concrete panels surface should be chiselled and roughened before pouring the new anti-seepage panels concrete, and then brush inorganic interface glue at the old and new concrete panels interface.

4.2 Panel combining technique with the original dam face
In order to ensure the reconstructed anti-seepage panels stable and secure, the reinforcement both take two kinds of methods including bottom bearing and combination of old and new panels, the second method of old and new panels combination includes bonded rebars post-anchoring technique and interfacial bonding technique.

4.3 Chemical bonded rebars post-anchoring technique
On the masonry gravity dam upstream, the reinforced concrete panels is 1.0m~1.46m thick. In order to ensure combination of the new and original concrete panels, the bonded rebars post-anchoring technique is taken at the interface, the row space of the anchor bars is all 1.5m, the inside of the anchor bars slant horizontally bellow with an angle of 5 degrees, the anchoring depth is 50cm, anchorage tensile strength is higher than 100kN. Anchorage construction procedure: surveying→drilling the holes with pneumatic drill→clean the holes with high-pressure pneumatic gun→checking and acceptance→mixing and pouring anchorage glue to be compact→anchor bars placement[4].

4.4 Interfacial bonding technique
In order to ensure a seamless bonding between the new and the original concrete anti-seepage panels, combining with chemical bonded rebars measure, the reinforcement also takes the measure of brushing inorganic interfacial glue at the interface between the old and new concrete structure. The first step is chiselling and cleaning the interface, and evenly brushing a layer of inorganic interfacial bonding glue, then pouring the reconstructed anti-seepage panels concrete. The technical specifications of the inorganic interface bonding glue are shown in Table 2, which tensile strength is higher than ordinary concrete[5].

| Performance                          | Index     |
|--------------------------------------|-----------|
| Compressive strength (MPa)           | 75.20     |
| Tensile strength (MPa)               | 5.10      |
| Shear strength (MPa)                 | 4.92      |
| Flexural strength (MPa)              | 14.20     |
| Interfacial bonding strength (MPa)   | 3.81      |
| Tensile strength of mortar ingredient (MPa) | 3.50 |
| Elastic modulus (MPa)                | 2.75×10⁴  |
| Linear expansion coefficient (10⁶ / ºC) | 12.0    |
| Impact toughness (J / cm²)           | 5.24      |

4.5 Panel parting and waterproof sealing technique

4.5.1 Waterproof sealing in the panels’ seams
In order to ensure vertical stability of the reconstructed anti-seepage panels, the panels bottom situate on the bedrock, the panels horizontal partings are construction cold joints, there are no gaps lefted in the joints, and the vertical steel rebars in the panels are through long steel rebars cross the horizontal
construction joints, that means the vertical rebars are not cut off at the joints. The horizontal parting of the panels are respectively located at the elevation of 180.9m, 190.0m and 202.6m.

The vertical partings of the new reinforced concrete anti-seepage panels upstream are cut through the vertical partings of the original dam body, the distance between the adjacent partings is in the range of 11.5m~14.75m. The vertical partings width of the new anti-seepage is 1.5cm, there are copper waterstop installed in the partings, the thickness of the waterstop is 1mm, and high pressure polyethylene closed cell foam is filled in the partings gap.

4.5.2 Sealing of the joints between the new and old concrete structural partings
The SR watershop is set up at the joints place between the new panels and the original protruding concrete structure of spillway piers or bottom emptying tunnel upstream water intake. The sealing structure is shown in Figure 4.

Figure 4. SR sealing structure at the joints place

The SR plastic filler performance is shown in Table 3[6]. The SR primer is matching adhesive for the SR plastic filler. The SR cover sheet is a reinforced anti-seepage cover sheet of ethylene propylene diene monomer (EPDM) rubber, which vertical and horizontal tensile strength is greater than 4.0MPa, and its elongation is greater than 350%.

Table 3. SR sealing plastic filler performance table

| Item                                | Test Conditions                  | Index   |
|-------------------------------------|----------------------------------|---------|
| Elongation at break (%)             | 10°C/-10°C/-40°C                 | 850/800/200 |
| Heat resistance (mm)                | 45 ° tilt, 80 °, 5h flow value    | <4      |
| The construction degree (mm)        | 25 °C, 5s, cone penetration value| 9 ~ 15  |
| Anti-permeability(MPa)              | 5mm thick, 48h impermeable water pressure | >1.5     |
| Freeze-thaw test (times)            | -20 ~ 20 °C cycle, not wrinkle and not crack | >300     |

4.6 Panel anti-crack technique
The vertical partings of the reconstructed anti-seepage panels are cut through the vertical partings in the original dam body, the distance between the adjacent partings satisfy the concrete deformation requirement, that benefits the panels’ anti-crack. Bidirectional steel rebars are distributed in the reconstructed panels surface layer, the typical reinforcement figure of the overflow section antiseepage panels is shown in Figure 5.
Figure 5. The typical reinforcement figure of a reconstructed anti-seepage panel

To improve the anti-seepage panels’ anti-crack performance, moderate monofilament polypropylene fibers are admixed into the reconstructed anti-seepage panels concrete, the diameter of every monofilament polypropylene fiber is in the range of 13μm–20μm, the length is not less than 20mm, the density is not less than 1.1g/cm³, the tensile strength is not less than 700N/mm², the elastic modulus is not less than 15000N/mm².

Admixing polypropylene fibers into the reconstructed anti-seepage panels can increase the ductility of the panels structure, reduce micro-cracks of concrete and prevent new crack’s propagation, that also can reduce temperature cracks and long-term shrinkage cracks, significantly enhance the anti-crack performance of the anti-seepage panels structure.

4.7 Panel anti-seepage, anti-freezing and anti-corrosion technique

The reconstructed panels have to bear more than 40m height of the waterhead, the concrete impermeability grade is required to achieve above W6 (60m waterhead).

The coldest month of the reservoir is January in winter, which average temperature is in the range of 4.6℃–5.3℃, therefore the reservoir belong to mild climate zone, taking account of the durability requirement, the concrete anti-freezing grade is required to achieve F100 (100 times circulation of freezing and thawing).

After analysis and discrimination of the reservoir water quality, it is identified the reservoir water have weak or moderate bicarbonate corrosion to concrete, ordinary portland cement with coal ash is used to improve concrete anti-corrosion capability in reinforcement construction process. The variety and quantity of cement, admixture and additive of concrete, water-cement ratio and air content ratio are all determined through test.

Moderately admixing polypropylene fibers into the reconstructed anti-seepage panels can directly enhance anti-crack performance, and also indirectly improve anti-seepage, anti-freezing and anti-corrosion performance.

4.8 Panel reconstruction and reinforcement effect

This project of the upstream anti-seepage panels reconstruction of the mansory gravity dam has been completed, after completion of the reconstruction project, a quality testing department has executed sample testing for the reconstructed anti-seepage panels’ quality, the testing has taken samples through drilling, the sampling items include compressive strength and anti-seepage grade of the anti-seepage panels concrete, there are 10 groups of concrete compressive strength sampling, every group of which has tested three times, and there are 6 groups of anti-seepage grade sampling. The 10 groups testing
value of compressive strength sampling are all higher than the standard value 16.7MPa of C25 concrete strength, the 6 groups testing value of anti-seepage grade are also all higher than design requirements, which satisfied quality requirements of the reconstructed anti-seepage design.

The reconstructed anti-seepage panels construction site situation of the masonry gravity dam before reinforcement, during reinforcement and after reinforcement is shown in Figure 6-8.

After the anti-seepage panels reconstruction and reinforcement, the masonry gravity dam has gone through quality testing and water storage commissioning test, the anti-seepage panels quality has satisfied design requirement, the leakage problems have been solved, and the appearance has been renewed, these have attained the expected effect of the reinforcement project.
5. Conclusion
A large number of masonry gravity dams have been built in our country have played significant roles for guarantee social development and satisfying people’s life requirements, many dams have gone through decades of operation, which have all generated varying degrees of leakage problem, reconstruction of upstream anti-seepage is a frequently adopted method to reinforce a masonry gravity dam, the keypoint of panels’ reconstruction is to solve the problems of their own structural stability, parting and sealing, anti-crack, anti-seepage, anti-freezing and anti-corrosion etc., and should take appropriate treatment measures to ensure structural stability, anti-seepage reliability and durability, in the past we have completed many masonry gravity dam reinforcement projects, from which we have explored the application of some reconstruction new techniques of anti-seepage panels, and have accumulated some relative technical experiences, and we hope to provide a reference for similar projects of anti-seepage reconstruction and reinforcement in future.

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