Comprehensive Waterproof Technical Research on Underground Fabricated Metro Station

Junjie Zhang 1, 2, *, Qingbiao Wang 1, 2, 3, 4, Qingkai Zhu 1, 2, Shuyi Xu 1, 2, Tangsha Shao 1, 2 and Qingli Kong 1, 2

1 Shandong Provincial Key Laboratory of Civil Engineering Disaster Prevention and Mitigation, Shandong University of Science and Technology, Qingdao 266590, China.
2 College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao Shandong 266590, China.
3 Department of Resource and Civil Engineering, Shandong University of Science and Technology, Tai’an Shandong 271019, China.
4 National Engineering Laboratory for Coalmine Backfilling Mining, Shandong University of Science and Technology, Tai’an Shandong 271019, China.

*Corresponding author e-mail: 27686942@qq.com

Abstract. With advantage in high-speed construction, prefabricated metro station becomes an important trend in the development of underground space structure. But there are only few researches on water seepage and leakage problems of prefabricated metro station, so it is of great importance to improve the waterproof construction technology. This paper makes theoretical analysis according to concrete structural self-waterproofing and studies the waterproof technology of fabricated metro station in tunnel. With showing the effect of comprehensive waterproof technology by project cases, the corresponding waterproofing measures can effectively solve the waterproofing problem of underground assembly Metro station, and provide technical reference for solving the leakage problem of Metro project.

1. Introduction
The waterproofing of underground fabricated metro station is one of the vital safety factors of manufacture, installation and operation in the whole metro station. The waterproof difficulty greatly increases because the underground fabricated metro station is the major structure to bear the load with facing huge hydraulic pressure.

Considering putting ability for shear of sprayed waterproof membrane between two linings, Vogel F[1] studied response measures to static loads between double-layer concrete lining and sprayed waterproof membrane. This double shell lining could be regarded as the comprehensive structure to be able to bear permanent load. Kang Y[2] analyzed the tunnel roof of Hong Kong-Zhuhai-Macao Bridge Seaside Tunnel and researched its stress state and waterproof measures; With using the combination technology of ground support bend roof and anti-freezing ground freezing, Zhang P[3] summarized its most challenging aspects and introduced the relevant waterproof technology applied in construction; A. Bobet[4] studied the influence of pore water pressure to tunnel waterproofing, and Sun R [5] studied the way how to combine the design and construction of underground waterproof engineering.
It can be seen that many scholars conducted a number of researches on waterproofing construction technology of underground engineering and a small number of researches on waterproof technology of prefabricated buildings. Some scholars just conducted overall waterproof researches on a part of underground fabricated buildings metro station, some just researched construction craft, some just carried on researches on waterproof materials, and some researched concrete structural self-waterproofing system and joint waterproofing process. While they didn’t probe into metro waterproofing with various comprehensive waterproof measures.

2. Water Seepage Mechanism of Concrete Structure
Concrete is the most common building material now, and it is a kind of complicated porous medium. The harmful ions in the environment can be transferred from concrete surface to structure interior \([6, 7]\) and then produce a series of physical and chemical reactions with cement dration pastes, which causes the durability problems of concrete structure. As for the penetrability of concrete, many scholars at home and abroad conducted a lot of researches, mainly on diffusion of chloride ions. For example, Buenfeld, et al. \([8]\) put forward the chloride ion penetration model involving coefficient diffusion and capillary effect; Boddy, et al. \([9]\) came up with a model considering such diverse mechanism as infiltration, diffusion, capillary effect and so on; Nillson presented a model \([10]\) which is about the invasion process of ions in concrete under the combined function of diffusion and atmosphere convection in unsaturated concrete.

In order to uncover the permeation law of water in soil body, French engineer Darcy summarizes Darcy Law which describes interrelation between osmotic energy loss and seepage velocity through plentiful tests and researches.

(1) Motion equation of pore water
Darcy analyzed a lot of test data and found that seepage flow \(q\) in the solid is in direct proportion to sectional area of cylinder \(A\) and head loss \(\Delta h\), and in inverse proportion to distance between fracture surfaces, and water seepage of concrete is less, which conforms to Darcy Law, that is:

\[
q = kA\Delta h / l = kAi
\]

Among the Formula (1), \(i\) is named hydraulic gradient; \(k\) is osmotic coefficient, \(cm/s\).

(2) Equilibrium equation of pore water

\[
\begin{align*}
\frac{\partial p}{\partial x} + \rho_s g \frac{v_x}{k_s} &= 0 \\
\frac{\partial p}{\partial y} + \rho_s g \frac{v_y}{k_y} &= 0 \\
\frac{\partial p}{\partial z} + \rho_s g \frac{v_z}{k_z} &= 0
\end{align*}
\]

Among Formula (2), \(k_s, k_y, k_z\) is the osmotic coefficient of solid body in different direction; \(v_x, v_y, v_z\) is the seepage velocity in different direction; \(p\) is pore water pressure.

(3) Continuity equation of pore water
Seepage continuity equation is Figured out according to conservation of quality of micro unit in percolation field:

\[
- \left[ \frac{\partial}{\partial x} (\rho_s v_x) + \frac{\partial}{\partial y} (\rho_s v_y) + \frac{\partial}{\partial z} (\rho_s v_z) \right] \Delta V = \frac{\partial}{\partial t} (\rho_n n \Delta V)
\]

Among the Formula (3): \(n\) is porosity of porous media.

(4) Seepage control equation of pore water
After plugging equilibrium equation of pore water into continuity equation, seepage flow
Mathematical model considering space compression of solid body can be worked out according to volume identity:

$$\nabla[k(\nabla p + \gamma_w)] = \gamma_n \beta_w \frac{\partial p}{\partial t} - \gamma_w \frac{\partial \varepsilon_v}{\partial t} \quad (4)$$

Among the Formula (4), $\nabla$ is gradient operator; $\beta_w$ is coefficient of volume compressibility of water; $\gamma_w$ is water weight; $\varepsilon_v$ is volume strain.

It is can be seen from Formula (1) to (4), water will permeate from the other of concrete necessarily as depth of penetration increasing over time. Actually, one side of concrete doesn’t connect through totally with the other side. Under the function of load, deformation and climate, water seepage of concrete is a chain reaction of water seepage at a early stage—degradation—cracking—permeability increasing, which finally leads to interconnection of seepage flow channel.

3. Research on Joint Waterproof property of Underground Fabricated metro station

To verify the applicability and durability of joint waterproof structure of tunnel prefabricated structure, the special waterproof property test on joint is conducted. According to anti-permeability requirement, the tests are divided into short-term anti-permeability test and long-term anti-permeability test. And meanwhile, the joint waterproof property can be reflected from side by water encounter swelling rubber deformation, the failure mode of joint waterproofing, joint open value and other relevant data[11].

The waterproof property experiment on prefabricated metro pipe joint aim at the joint waterproof structure of tunnel prefabricated structure of track 2 Changchun metro in China, adopting 1:1 full-scale model test pieces. As is shown in Figure 1, the test piece consists of seven prefabricated standard pipe joint of utility tunnel and is assembled to sealed module by prestress. Among the test piece, standard pipe joint is adopted the assembly pattern with longitudinal and transverse joints. The strength and waterproofing grade are C40 and P10 respectively. The material components and cross sectional dimensions of water encounter swelling rubber are optimized and determined by experimental results at the early stage. The sketch of water encounter swelling rubber and its physical mechanical properties parameter are shown in Figure 2. The partial joint of prefabricated component is as shown in Figure 3.

![Figure 1. Dimension sketch of prefabricated component](image1)

![Figure 2. Water encounter swelling rubber](image2)

![Figure 3. Partial joint of prefabricated component](image3)
3.1. Short-term Waterproof Test
The test is conducted on the joint waterproof properties of water encounter swelling rubber in the short time at the stage of incomplete expansion. The specific test procedures are as follows: ① Install and put the test piece in place and exert transverse and longitudinal prestress to the designed value. The transverse prestress is exerted on the central section of metro station and the longitudinal prestress on the four corners of cross section; ② Add water and pressure to sealed metro station through roof water inlet.

It can be found from test that: (1) When longitudinal prestress is up to the designed value, that is, \( \sigma_{\text{con}} = 540 \text{MPa} \) and \( \sigma_{\text{pe}} = 460 \text{MPa} \), the hydraulic pressure in pipeline cabin can maintain in the designed value 2h, and there is no water seepage in roof and base. (2) When reducing the longitudinal prestress generally to \( \sigma_{\text{con}} = 440 \text{MPa} \) and \( \sigma_{\text{pe}} = 380 \text{MPa} \), the roof joint of test piece begins to seep water slightly. But seepage discharge is very small. The hydraulic pressure in pipeline cabin can maintain in the designed value for a long time. (3) As longitudinal prestress decreasing continuously, the seepage of test piece joint aggravates. When \( \sigma_{\text{con}} = 290 \text{MPa} \) and \( \sigma_{\text{pe}} = 240 \text{MPa} \), the roof joint begins to seep seriously. At this time, the base joint begins to seep slightly and the hydraulic pressure in pipeline cabin can not reach the designed value. Then the test ends by that time.

3.2. Long-term Waterproof Test
The test is conducted on the joint waterproof properties of water encounter swelling rubber in the long time at the stage of incomplete expansion. Its specific test procedures are same with that of short-term test. It can be found from test that: (1) Compared with short-term waterproof test, water encounter swelling rubber is found obvious expansion phenomenon and some parts of it expands towards lateral exceeding the reserved groove boundary partially. (2) Tester should make the longitudinal prestress value be same to the value when short-term waterproof test ends. When the hydraulic pressure in pipeline cabin is up to the designed value, test piece roof seeps slightly. And the waterproof effect of long-term waterproof test is better than that of short-term test. (3) Reducing the longitudinal prestress generally, the seepage of test piece joint aggravates. When \( \sigma_{\text{con}} = 190 \text{MPa} \) and \( \sigma_{\text{pe}} = 160 \text{MPa} \), test piece roof joint begins to seep seriously and the hydraulic pressure in pipeline cabin can not reach the designed value. Then the test ends by that time.

3.3. Failure Mode of Joint Waterproofing
The joint of underground fabricated metro station has good waterproof performance and long-term waterproof performance is obviously better than short-term waterproof performance. Therefore, the joint waterproof design of prefabricated utility tunnel can adopt elastic sealing principle. The failure process and form of joint waterproofing in underground fabricated metro station are as shown below.

| Test situation | Tension controlled stress \( \sigma \) (MPa) | Effective prestress \( \sigma \) (MPa) | Joint sketching value (mm) | Failure mode of joint waterproofing |
|----------------|---------------------------------|---------------------------------|-----------------------------|-----------------------------------|
| Short-term waterproof test | 540 | 460 | 11.87 | No seepage |
| | 490 | 420 | 12.15 | No seepage |
| | 440 | 380 | 12.62 | Slight seepage of roof joint |
| | 390 | 330 | 12.92 | Slight seepage of roof joint |
| | 340 | 290 | 13.22 | Slight seepage of roof joint and slight seepage of base joint |
| | 290 | 240 | 13.50 | Serious seepage of roof joint and slight seepage of base joint |
| Long-term waterproof test | 290 | 240 | 13.57 | Slight seepage of roof joint |
| | 240 | 210 | 13.85 | Slight seepage of roof joint |
| | 190 | 160 | 14.20 | Serious seepage of roof joint and slight seepage of base joint |

Table 1. Failure process and form of joint waterproofing
3.4. The Deformation of Water Encounter Swelling Rubber

It is known from the previous section that the deformation of water swelling rubber is balanced during the process of exerting longitudinal prestress, indicating that the force water encounter swelling rubber suffers is balanced in longitudinal joints under the function of longitudinal four-corner prestress. So the pressure water encounter swelling rubber bears per unit length can be counted according to Formula (5):

$$N = \sum N_{pe} / l$$  

Among Formula (5), $N_{pe}$ is sum of longitudinal effective prestress; $L$ is overall length of swelling rubber in longitudinal joints.

The test joints aren’t closed during the whole test and water encounter swelling rubber bears the prestress totally, indicating that the change of test joint open value is the deformation of water encounter swelling rubber. The calculation Formula (6) of fitting curve is as follows:

$$N = 11.5\Delta + 5\Delta^2$$

Among Formula (6), $N$ is the pressure of water encounter swelling rubber; $\Delta$ is the deformation of water encounter swelling rubber.

It is shown from the short-term waterproof test of joints, when longitudinal prestress value is over 440MPa, the prefabricated assembly joints have good waterproof performance. At this time, the pressure of water encounter swelling rubber in the place of base joint is 65kN/m, and the overall deformation of water encounter swelling rubber is 2.93mm. For safety, the minimum pressure of this kind of water encounter swelling rubber is 75kN/m to ensure the joints have good waterproof performance, and meanwhile the compressive deformation of water encounter swelling rubber is about 1.5mm known from the relationship between the pressure of water encounter swelling rubber and its deformation.

4. Engineering Application

4.1. Project Profile and Hydrogeological Condition

Xixing station, Changchun metro is underground two-storey cut and cover metro. Its frame structure is single column- double span, and construction method is cut and cover method. The cast-in-situ method is adopted in the shield receiving well and shield starting well, and its building envelope adopts $\Phi1000@1500$ cast-in-situ bored pile and $\Phi609/800$ steel tube inner support system; The assembly method is adopted in central standard section, and its building envelope adopts $\Phi1000@1400$ drilling piles and anchor cable support system. The thickness of covering soil of roof is about 4.3m, floor deep standard section is 22.7m and the length of foundation trench is 277.9m.

The depth of groundwater level is very shallow. The groundwater depth is 1.80 ~ 4.10m and elevation is 218.37 ~ 224.20m in investigation period. And the groundwater is mainly in the fourth cohesive soil layer. There is no big differences between horizontal permeability and vertical permeability. And the mean of change over several years is 1.50m, the maximum water level is 1.00m in the past three to five years, so the highest water level on records can be considered as 1.00m.

4.2. Joint Waterproofing of Component

4.2.1. Caulking waterproofing. Joint interior of vault component is filled with water encounter swelling water-stop rubber and polymer cement mortar. Three water-stop rubber layers are set in the place of anchor head outside the joint to seal it. And waterproof paint and non-woven are adopted on the surface. The joints are strengthened to ensure no seepage or leakage at later stage. The vault caulking waterproofing is as shown in Figure 4.
4.2.2. Seal gasket waterproofing. There are two seal gaskets in the upstream face and downstream face of component to be waterproof [12, 13]. The compound EPDM rubber elastic seal gasket is stuck in groove of seal gasket to be waterproof by being compacted and swelling when encountering water. In order to ensure the seal gasket contact width of two sides of joint, the circular seam faulting of slab ends value of component is not more than 5mm, and faulting of slab ends rate is not more than 10%. Angular position of seal gasket is easy to seep water, so it is required that angular position brushed lubricant can be squeezed into groove and remain undamaged when being squeezed and sliding; At the same time, the 1.5mm-thick butyl rubber putty pieces is required to be struck on angular position to strengthen waterproofing. And the two sides of putty piece temples is not less than 150mm. All longitudinal joints need painting lubricant, and silicone oil lubricant is better to be adopted.

4.2.3. Grouting waterproofing. The grouting system is installed in the place of joint of assembly structure to conduct structure strengthening and waterproofing. Before grouting, field test is required to be conducted ahead of time and the grouting project should be accepted by every party, and the layout of grout pipe is as shown in Figure 5. As for the component joint mortise part, the A and B parts 2–4 loop in starting section needs grouting timely, and the other sections should be adjusted according to the structural stability and test situation after the structure becoming a ring formation. Angular position of component joint should be installed over 20mm-thick EPDM sponge rubber to be blocked. The four sides of all broaching should be set 20mm-thick sponge rubber to be blocked. And prefabricated components adopt double-side waterproofing. Compound EPDM rubber elastic seal gasket has to be placed in groove to conduct waterproofing by squeezing and swelling encountering water. Meanwhile, the seal gasket contact width of two sides of joint should be controlled strictly to ensure that circular seam faulting of slab ends value of component is not more than 5mm and faulting of slab ends rate is not more than 10%.

Angular position of seal gasket is easy to seep water, so it is required that angular position brushed lubricant can be squeezed into groove and remain undamaged when being squeezed and sliding; At the same time, the 1.5mm-thick butyl rubber putty pieces is required to be struck on angular position to strengthen waterproofing. And the two sides of putty piece temples is not less than 150mm. All longitudinal joints need painting lubricant, and silicone oil lubricant is better to be adopted. There should be remedy approach when seal gasket is damaged slightly.
M20 cement mortar or epoxy mortar can be used to fill the joints of side wall. Before filling, the joint interspace should be cleaned by high-pressure water to ensure the compacted and complete connecting between side walls of concrete, which is as shown in Figure 6 and Figure 7.

![Figure 6. The laying of ring cushion layer](image1)

![Figure 7. Compacted concrete side walls](image2)

Water encounter swelling rubber can be used for horizontal and longitudinal construction joints. Before injecting glue, waterproof material needs brushing. As for circumferential construction joints, galvanized steel sheet sealing belt should be set according to the position based on flowing section.

As for the deformation construction joints, there are three procedures to take the waterproof measures in the outer, centre and interior, that is, waterproof material should be struck outside the joints, the rubber sealing belt should be struck on the contacted part of central duct piece and the portable sealing belt can be adopted in the inner deformation construction joints.

4.3. Waterproof Control Elements

According to all construction emphasis and technical problems in construction, the quality control should be conducted from such aspects as concrete structural self-waterproofing of component, seal gasket sticking, grouting waterproofing, processing demands of base and single-package polyurethane coating waterproof layer:[14,15]

1. Net protecting thickness of reinforced concrete outside component should not be less than 50mm;
2. After sticking seal gasket, the seal gaskets of four corners of duct piece mustn’t be collapsed or warped;
3. When the construction is in rainy season, the water encounter swelling rubber will swell when encountering water. So the lubricant for slowing swelling speed should be brushed on the surface of water encounter swelling rubber products to ensure that there is no swelling ahead of time in assembly process;
4. Angular position of component joints should be installed over 20mm-thick EPDM to be blocked, and sponge rubber ends should connect with EPDM gland to avoid grout runout;
5. According to the design requirements, cement mortar at the ratio of 1:2.5 should be used in internal corners to be made into $5 \times 5$cm obtuse angle or over 5cm circular bead. And all external corners should be made into $1 \times 1$cm obtuse angle or over 1cm circular bead;
6. When constructing polyurethane coating waterproof layer, the protecting layer of waterproof layer should be made in advance adopting 2cm-thick foam board, and the foaming ratio had better to be about 30 times of all foam plastic material.

5. Conclusion

(1) It is found from the joint waterproof research of underground fabricated metro station prefabricated component that in short-term waterproof test, hydraulic pressure can maintain the designed value 2h, and there is no seepage in roof and base joints; Compared with short-term test, there is obvious swelling of water encounter swelling rubber and water encounter swelling rubber has obvious feature of nonlinear deformation; Tester should make the longitudinal prestress value be same to the value when short-term waterproof test ends. When hydraulic pressure reaches designed value, the test piece roof joint begins to seep slightly. And the waterproof effect of long-term waterproof test is better than that of short-term test.
(2) According to the requirements of concrete structural self-waterproofing of component, the relevant waterproof measures such as seal gasket waterproofing, caulking waterproofing and grouting waterproofing and three procedures in the outer, centre and interior are adopted to ensure that circular seam faulting of slab ends value of component is not more than 5mm and faulting of slab ends rate is not more than 10%, further meeting the requirements of concrete structural self-waterproofing of component; According to the field engineering practice, the research of composite waterproofing principle solves fabricated metro waterproof problem under high confined water head in water-rich clay stratum.

References

[1] Vogel F, Sovják R, Pešková Š. Static response of double shell concrete lining with a spray-applied waterproofing membrane[J]. Tunnelling and Underground Space Technology, 2017, 68: 106-112.

[2] Kang Y, Liu Q, Cheng Y, et al. Combined freeze-sealing and New Tubular Roof construction methods for seaside urban tunnel in soft ground[J]. Tunnelling & Underground Space Technology, 2016, 58:1-10.

[3] Zhang P, Ma B, Zeng C, et al. Key techniques for the largest curved pipe jacking roof to date: A case study of Gongbei tunnel[J]. Tunnelling & Underground Space Technology, 2016, 59:134-145.

[4] Bobet A. Effect of pore water pressure on tunnel support during static and seismic loading[J]. Tunnelling and Underground Space Technology, 2003, 18(4): 377-393.

[5] Sun R. How to Design and Construct the Underground Waterproofing Project in Combination[J]. World Construction, 2017, 6(3).

[6] Nilsson L O. A numerical model for combined diffusion and convection of chloride in non-saturated concrete[C] Second International RILEM Workshop on Testing and Modelling the Chloride Ingress into Concrete. 2001: 261-275.

[7] ZENG Ge-hua , XIA Cai-chu. Effect of radial erection error of segments on waterproofness of segment rings of shield tunnels[J]. Chinese Journal of Geotechnical Engineering,2016,38(11):2017-2025.

[8] LIU Jianguo  WANG Wenyuan. Analysis on Waterproofing Design and Erection Parameter for a Quasi-Rectangular Shield Tunnel [J]. Modern Tunnelling Technology,2016,53(S1):151-157.

[9] Poon C S, Shui Z H, Lam L. Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates[J]. Construction and Building Materials, 2004, 6(18): 461-468.

[10] Tian Zixuan. EXPERIMENTAL RESEARCH ON FORCE PERFORMANCE OF PRECAST CONCRETE

[11] UNDERGROUND COMPREHENSIVE MUNICIPAL TUNNEL [D]. Harbin Institute of Technology,2016.

[12] DONG Lin-wei JIANG Yu-sheng YANG Zhi-yong CHENG Jin-guo LIU Chao-qun ZHANG Jia-jian. Experimental study and water-resistant mechanism of gaskets in joints of tunnel segments [J]. Chinese Journal of Geotechnical Engineering,2017,39(03):469-474.

[13] TUO Yong-fei,SHU Heng,GuO Xiao-hong,DING Wen-qi,WANG Jian. Design and experimental study on waterproof gasket of large-diameter shield tunnel under ultra high water pressure[J]. Chinese Journal of Geotechnical Engineering,2013,35(S1):227-231.

[14] LI Peng ZHANG Qing-song ZHANG Xiao LI Shu-cai ZHANG Wei-jie LI Meng-tian WANG Qian. Analysis of fracture grouting mechanism based on model test [J]. Rock and Soil Mechanics,2014,35(11):3221-3230.

[15] LI Shu-cai , ZHANG Wei-jie, ZHANG Qing-song ,ZHANG Xiao ,LIU Ren-tai ,PAN Guang-ming ,LI Zhi-peng , CHE Zong-yuan . Research on advantage-fracture grouting mechanism and controlled grouting method in water-rich fault zone [J]. Rock and Soil Mechanics,2014,35(03):744-752.