Study on Water Flow Control Standard of Ultra LongUndermarine Tunnel by Drilling and Breaking

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Abstract: For ultra long undermarine tunnel by drilling and breaking, it is often difficult to bear the all-inclusive waterproof lining structure, and limited emission measures are generally adopted. The reasonable leakage standard is the key to the reasonable balance between the cost of grouting plugging and the pumping and drainage cost during the operation period. Based on the penetration coefficient control analysis and the different applicability of different pre-grouting control measures, the applicable standards of pre-grouting control measures are formulated based on the advance drilling water inflow, pressure and rock formation conditions. The pre-grouting stop standard can consider the further control effect on the basis of the leakage control standard, and the radial grouting stop standard should be properly strict in the subsequent long-term effect.

Key words: submarine tunnel leakage control standard pre grouting

1. Preface
A proposed submarine tunnel is about 15 km long, including the tunnel is about 10 km long in the middle sea section, the tunnel is arranged in parallel with the double main tunnel + service tunnel, the main tunnel one-way three-lane width is about 15 m, two-way service tunnel is about 8m. The maximum water head of the tunnel is about 150 m, the buried depth of the middle part of the sea is more than 60m. The tunnel is mainly located in igneous strata, half of granite and half of tuff. The tuff section of the tunnel is located in the secondary influence zone of the fault, and the fractures are developed.

The geological conditions of Jiaozhou Bay Subsea Tunnel are the same as those of the project. The grouting control scheme [18] is proposed. The grouting start standard is introduced in detail, but the grouting end standard is not determined. Qingdao Metro Line 8 is also similar. For long tunnels, it is necessary to systematically determine the water leakage control system. First, the water leakage control standard should be determined, then the start standard and end standard of water leakage control measures should be determined, and the water leakage should be controlled by sections according to geological conditions.

According to relevant design experience, the underground tunnel buried depth of more than 60m is all-inclusive waterproof and not economical. Therefore, the tunnel plans to use limited emissions measures to control the groundwater leakage, but several problems need to be solved:
(1) How to reasonably determine the average water leakage control standard of the tunnel;  
(2) How to take effective measures to control the water leakage;  
(3) How to control the leakage of tunnel section;  
Relevant research and analysis were carried out for these problems.  

2. Study on average leakage water standard  
According to relevant documents, the leakage control standards of some tunnels are shown in the following table:  

| Allowable Water Inflow Limit                                                                 | Notes                                                |
|---------------------------------------------------------------------------------------------|------------------------------------------------------|
| <2 L/min / 100 m (Finnish Standard, Sievanen et al., 2012)                                  | For Critical areas in Road/Railway Tunnel            |
| 2-4 L/min / 100 m (Norwegian Standard, Norwegian Tunneling Society, 2011)                   |                                                      |
| 2-10 L / min/100 m (Norwegian Standard, Grøv et al., 2012)                                  |                                                      |
| 2-5 L / min / 100m (Swedish Experience)                                                     |                                                      |
| <20 L/min per 100 m (General, Kristin and Nilsen, 2014)                                     |                                                      |
| <30 L / min per 100 m (Subsea Tunnel, Blindheim and Oevstedal, 2002)                        | Subsea Tunnels                                       |
| 10-30L / min/100m (Subsea Tunnel, Grøv et al., 2012)                                       |                                                      |
| Typically 5 – 50 L/min / 100 m (Guidance Note on Pre-Excavation Grouting for Underground Construction in Hard Rock, Association of Geotechnical & Geo-environmental Specialists, Hongkong) |                                                      |
| <7-14 L/min / 100 m (T-Baneringen Metro Tunnel, Stage One, Norway, Excavation completed 2002) |                                                      |
| <1020 L/min / 100 m (Lunner Road Tunnel, Norway, Excavation completed 2002)                 |                                                      |
| <4-16 L/min / 100 m (Skaugum Railway Tunnel, Norway, Excavation completed 2004)              |                                                      |
| <10-20 L/min / 100 m (Storsand Road Tunnel, Norway, Excavation completed 2004)              |                                                      |
| <1-2 L/min / 100 m (ONKALO Project, Finland)                                                |                                                      |

Generally speaking, the leakage standard is too loose, which will lead to increase in pumping and drainage cost, too strict, and increase in construction cost. Since the middle sea length of the project reaches 10 km and mainly adopts drilling and explosion method, leakage control is difficult, so the international relatively loose leakage control marks 30 L /min/100m, is 0.4 m³/ (m.d) serves as the average water leakage control standard for this tunnel.  

3. Study on Leakage Control Standard  
The average leakage water is multiplied by the length of the tunnel, the total leakage quantity of the whole tunnel, but requires section control in tunnel construction, especially after composite lining, it is difficult to control groundwater leakage. Therefore, the leakage inspection standards need to be determined in sections, which needs to be determined according to the geological conditions and leakage control measures. Study on leakage water inspection standards for different grouting measures and formation conditions.  
According to the geological survey report, the tunnel crossing strata of the sea section mainly include: bedrock weakly weathered zone, microweathered broken rock (including fracture zone) and bedrock
microweathered zone. The permeability is related to the elegance degree of the rock stratum and the stratum conditions. The main stratum permeability is shown in the following table:

Table 3-1 Penetration Coefficient and Permeability of Main surrounding Rock in Marine Section

| Lithology                                      | Penetration coefficient (m/d) | Permeability       |
|-----------------------------------------------|------------------------------|-------------------|
| Weak weathered zone of bedrock                | 0.036~0.150                 | Weak permeable    |
| Microweathered and crushed rock (Including the fracture zone) | 0.003~0.144                 | Micro ~ weak permeable |
| Microweathered zone of the bedrock            | 0.001~0.134                 | Weak permeable    |

According to the permeability size of the tunnel, in order to meet the leakage control standard, it is necessary to take different leakage control measures. Drilling and blasting tunnel generally adopts advance pre-grouting and radial grouting measures after excavation to control the leakage water. In order to theoretically analyze the effect of seepage control measures, the grouting effect around the tunnel is idealized grouting ring, assuming that the tunnel surrounding rock, grouting reinforcement ring and shotcrete are isotropic uniform continuous medium; the tunnel is circular, the water flow is stable flow, the movement law follows the Darcy theorem, and the calculation model of tunnel drainage volume can simplify the following figure:

Fig. 3-1 Simplified model of drainage volume and water pressure

According to the groundwater dynamics theory, the water pressure \( P \) of the initial branch surface of the tunnel drainage volume \( Q \), and the water pressure \( P_g \) outside the grouting reinforcement circle comply with the following formula:

\[
Q = \frac{2\pi H r_2}{\ln \frac{r_2}{r_1} + \frac{k_r}{k_g} \ln \frac{r_2}{r_1} + \frac{k_r}{k_r} \ln \frac{r_1}{r_0}};
\]

\[
P = \gamma h_1 = \frac{\gamma H \ln \frac{r_1}{r_0}}{\ln \frac{r_1}{r_0} + \frac{k_r}{k_g} \ln \frac{r_2}{r_1} + \frac{k_r}{k_g} \ln \frac{r_g}{r_1}};
\]
\[ P_{gw} = \gamma h_g = \frac{\gamma h_1 \ln \frac{r_2}{r_1} + \frac{\gamma h_1}{K_1} \ln \frac{r_2}{r_g} + \frac{K_1}{K_2} \ln \frac{r_2}{r_0}}{K_1 + \ln \frac{r_2}{r_1} + \frac{K_1}{K_2} \ln \frac{r_2}{r_g} + \frac{K_1}{K_2} \ln \frac{r_2}{r_0}}; \]

Q—Tunnel Drainage Volume (m$^3$/s);
P—initial water pressure (kPa);
P$g$—Water pressure outside the grouting reinforcement circle (kPa);
K$r$—surrounding rock penetration coefficient (m/s);
K1—initial support penetration coefficient (m/s), reference $6.5 \times 10^{-3}$ m/s;
k—grouting body penetration coefficient (m/s);
H—Water level difference between the groundwater level and the circular center of the tunnel (m);
r0—Radius (m), 7.6 m;
r1—Radius (m), 7.9 m;
r2— is a far-field distance, equal to H;
gr—Outer radius (m) of the grouting reinforcement circle;
$\gamma$—Weight of water(kN/m$^3$), Take the 10 kN/m$^3$.
h1—line head of outside surface (m);
h$g$—Water head outside the grouting reinforcement circle (m);
E—Thickness of the grouting reinforcement ring (m), E=r$g$-r1;
r$g$=r1,P=P$g$. when the tunnel is reinforced without grouting.

It is known from the above formula that at the same groundwater head (sea level), the penetration coefficient of the surrounding rock increases, the drainage volume of the tunnel increases, and the tunnel lining water pressure P increases. The grouting penetration coefficient is the key parameter to reflect the effect of leakage control measures. According to relevant research, economical and reasonable ordinary cement grouting is selected. The penetration coefficient of the grouting circle is $1/50$ of the surrounding rock penetration coefficient, but the moderately weathered conglomerate bearing sandstone are relatively large, and the conventional grouting cannot meet the limited discharge requirements. The drainage volume will increase the maintenance cost of the later operation period. Therefore, for the relatively large permeability parameters of fracture rock, fault crushing zone and other strata, multiple grouting and other processes should be adopted, and grouting materials such as ultra-fine cement single slurry, special sulfur aluminate cement single slurry, ordinary cement-water glass double grouting are adopted to further reduce the penetration coefficient of the reinforcement circle and control the leakage of the surrounding rock.

Select the most typical lowest point of the tunnel, and calculate the non-grouting, $3m, 5m$ and $7m$ reinforcement circle, the initial supporting drainage and external water pressure of the tunnel. The calculation results are shown in Table 3-1.

### Table 3-2 Comparison of Drainage and External Water Pressure of Different Round Rock

| Round rock permeability (m/d) | No grouting | 3 m Ordinary grouting reinforcement ring | 5 m Ordinary grouting reinforcement ring | 7 m Ordinary grouting reinforcement ring |
|------------------------------|-------------|----------------------------------------|----------------------------------------|----------------------------------------|
| Drainage capacity (m$^3$/dm) | Water pressure: MPa | Drainage capacity (m$^3$/dm) | Water pressure: MPa | Drainage capacity (m$^3$/dm) | Water pressure: MPa | Drainage capacity (m$^3$/dm) | Water pressure: MPa |
|------------------------------|-------------|----------------------------------------|----------------------------------------|----------------------------------------|
| 0.001                        | 0.27        | 0.30                                   | --                                    | --                                    | --                        | --                        | --                        |
| 0.005                        | 0.78        | 0.85                                   | 0.23                                  | 0.25                                  | --                        | --                        | --                        |
| 0.008                        | 0.95        | 1.04                                   | 0.33                                  | 0.36                                  | --                        | --                        | --                        |
| 0.01                         | 1.02        | 1.11                                   | 0.39                                  | 0.43                                  | 0.30                      | 0.33                      | --                        |
| 0.03                         | 1.28        | 1.40                                   | 0.42                                  | 0.46                                  | 0.31                      | 0.34                      | --                        |
It can be seen that without grouting measures, the surrounding rock permeability reaches 0.001 m/d. According to the geological data provided, leakage control measures for the whole tunnel, using local grouting, 3 m~7 m reinforcement circle or special grouting process and grouting materials, the tunnel drainage can be controlled at 0.2~0.5 m²/d.m.

The typical values of permeability coefficient of weak weathering, moderate weathering, and strong weathering (crushing zone) are 0.01 m/d, 0.1 m/d, 0.5 m/d respectively, and the corresponding inflow of theoretical tunnel is 10 times and 50 times. Considering grouting control, the leakage control standard is recommended to be 2 and 4 times. The proportion of weak weathering, moderate weathering and strong weathering (broken zone) corresponds and surrounding rock, roughly: 7: 2: 1. Considering the worse the surrounding rock, the harder the leakage control, the greater the cost. But at the same time, it must meet the goal of 0.4 m³ per linear meter, it is suggested that the water leakage control standards of weak weathering, medium weathering and strong weathering (fracture zone) should be 0.2 m³, 0.4 m³ and 0.8 m³ per linear meter respectively.

4. Standard Study on water leakage control Measures

4.1. Pre-grouting control standard

In order to meet the leakage control standards, reasonable leakage control measures need to be taken during the construction process. During the construction of drilling and blasting tunnel, the geological conditions of the front surrounding rock are first determined according to the advance geological prediction system, and then appropriate pre-grouting control measures are selected. The advance geological crushing system is analyzed through the advance geological forecasting system, mainly using the TSP advance geological prediction system and the advance geological drilling. According to the geological forecast size of groundwater permeability and the stability of surrounding rock, the water gushing or water seepage around the tunnel excavation section is blocked outside the structure by advance grouting. Microweathered rock layers with good rock mass integrity shall be blocked without grouting, partial grouting plugging water or radial grouting plugging water. In the fault crushing zone and other areas, in addition to the advance grouting to reduce the permeability coefficient of the reinforcement circle, the groundwater circulation channel should be further closed by supplementary radial grouting or local grouting, reduce the groundwater infiltration, and strengthen the setting of the drainage system to reduce the water pressure acting on the lining.

Investigate the construction experience of many projects, and put forward the following pre-grouting suggestions.

| Grout scheme | ApplConditions |
|--------------|----------------|
| Full-section grouting | ① The length of the fault zone is more than 25m, the rock mass in the fault zone is |
broken, the weathering is serious, or there is fault gouge interlayer, which may cause water and mud inrush; ② The water output of single hole of advanced water detection drilling is more than 50 L / min, the total water output of all holes is more than 100 L / min or the water pressure of water detection hole is more than 0.6 MPa.

Curtain grouting around the tunnel

① The length of the fault zone is less than 25 m, and the surrounding rock in the fault zone is broken or weathered seriously; ② The water output of single hole is 15-50 l / min, the total water output of all holes is 30-100 l / min, or the water pressure of water exploration hole is 0.3-0.6 mpa.

Advance grouting of local section

① The surrounding rock of partial section of the tunnel is relatively broken or the joints and fissures are relatively developed, while the surrounding rock of other parts is relatively complete. ② The water output of single hole is 5-15 l / min, the total water output of all holes is 10-30l / min, or the water pressure of water exploration hole is less than 0.3MPa.

Note: The probe length is calculated as per 30m.

A large number of engineering practices show that the pre-grouting measures are the key to the realization of the leakage water control standards, because the radial grouting water control of leakage water after excavation is much more difficult than the pre-grouting control measures. In order to control the leakage water, after the pre-grouting, it is necessary to set inspection holes to check the leakage situation. This standard is the key to leakage control. According to the research, the countries is slightly different. The typical standard are as shown below:

Table 4-2 Trigger Value of Water Inflow from Probe Holes for Grouting Corresponding to Limit of Residual Inflow

| Limit of Residual Inflow (L/min / 100m) | Inflow Measured from probe holes (L/min) | Note |
|----------------------------------------|----------------------------------------|------|
|                                        | Single Hole                            | All Holes |                  |
| 15                                     | >1                                     | >3        | No rw egian recommendation f o r tunnel construction (Note: f o r probe hole not less than 20 m long) |
| 30                                     | >2                                     | >6        | Guidance Note on Pre-Excavation Grouting f o r Underground Construction in Hard Rock,Hongkong |
| 50                                     | >4                                     | >10       |                  |
| 5-50                                   | 0.1-5                                  | -         |                  |
| 15                                     | 1                                      | 3*        | Harbour Area Treatment Scheme Stage 2A (HATS2A), Hongkong, Garshol et al. 2014 |

* for any group of 4 holes

The tunnel length of the project is large and the leakage water expected is high, so the strict drilling gushing standard is adopted. The tentative grouting stop standard is: according to the standard of 0.15L/min per delay meter or the inflow of local hole is less than 3 L/min (the length of inspection hole is calculated as 20m).

4.2. Radial grouting control standards

Even if pre-grouting measures are taken, there is still water leakage after the completion of tunnel excavation, and radial grouting measures are needed to further control the tunnel leakage water volume, similar to pre-grouting, the start standard and end standard need to be determined. Referring to similar engineering cases, radial grouting startup standard: leakage point into line flow or mud sand, or average leakage greater than 4.5 L / (m²d), or any 5m length of water leakage greater than 1.0m³/ d. Radial grouting end standard: water leakage is not allowed, there can be a little wet stains on the
structure surface, and the average water seepage amount is not more than 2 L/ (m$^2$·d), or any 5 m length of water leakage greater than 0.25 m$^3$/d.

4.3. Selection criteria for grouting materials
Ordinary cement slurry is the most commonly used grouting blocking material, but for large water inflow, ordinary cement slurry control capacity is limited, at this time such as cement water glass or polyurethane and other special slurry needs to use for control, for the need to strictly control the leakage, super fine cement should be used to improve the permeability of the slurry, so as to improve the leakage control effect. The following are the reference standards for the selection of grouting materials based on practical experience.

For the advance grouting measures: (1) when the water yield of single hole is less than 50 L / min, the ultra-fine cement single slurry is used. (2) When the water yield of single hole drilling is 50-100 L / min, it is selected according to the sequence of ordinary cement slurry → ultra-fine cement slurry. (3) When the water yield of single hole drilling is more than or equal to 100 L / min, it shall be selected in the order of double slurry → sulphaolunate slurry → ordinary cement slurry → ultra-fine cement single slurry.

For radial and local grouting: be selected in the order of → superfine cement single slurry, and adopt special grouting materials such as modified polyurethane if necessary.

5. Research conclusions
Through the investigation of similar engineering cases, through theoretical analysis and in combination with the project characteristics, this paper proposes the water leakage control standards and control standards of the project. The main standards are as follows:
(1) Use of 30L /min/100m, or 0.4 m$^3$/ (m.d) As the average leakage control standard for this tunnel, the tunnel limited emission standard is 0.2~0.8m$^3$/ (m.d).
(2) The start-up and end standards of tunnel pre-grouting are proposed.
(3) Referring to similar engineering experience, the selection standard of grouting materials are proposed.

The project has not been constructed yet. The proposed leakage control standard will guide the implementation of the project, and can also provide reference for similar underwater tunnel projects. Through the accumulation of practice, the control standard can be optimized.

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1 References are unmarked in the paper.
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