NUMERICAL STUDY ON HORIZONTAL PRE-DRAINAGE SYSTEM USING HORIZONTAL DIRECTIONAL DRILLING IN SUBSEA TUNNELLING

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Abstract：An effective pre-drainage system in a limited area that has a high water head and huge inflow is important to prevent flooding accidents during subsea tunnelling. Most of collapses in subsea tunnels are associated with huge inrushes of water due to high water head and flows through faults. To find out the causes and countermeasures for flooding cases，a dozen of cases for TBM and NATM tunneling are studied. Case studies presented here show that if the leakage had been forecasted and pre-drained prior to the tunnel excavation，such accidents could have been prevented. In this study，a new horizontal pre-drainage system is suggested. Numerical analyses are performed to analyze the water head controlling effect on the tunnel face by drainage holes during the construction of subsea tunnels. It is supposed that the rock cover of a subsea tunnel is 100 m，and the depth of seawater is 60 m. Drainage system analyses are performed to analyze performance of the drainage system. The total head after horizontal pre-drainages，when the permeability of the ground is 0.0036 m/h，reduces to about 60% at the tunnel crown and 53% at the tunnel spring line. When the radius of the drainage pipe is 5 cm and the permeability of the ground is 0.0036 m/h，the length of the pipe should not exceed 250 m to maintain the drainage performance. Numerical analysis and a drainage performance analysis both show that the suggested horizontal pre-drainage system provides a clear drainage and water head reducing effect. The system is a new alternative to the present water controlling methods applied to subsea tunnels.

Key words：subsea tunnel；drainage system；flooding；horizontal directional drilling；leakage

CLC number：U 459.5 **Document code**：A **Article ID**：1000－6915(2007)增 2－3697－07

水平向钻孔的海底隧道横向预排水系统数值模拟

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Received date：2007－06－21；**Revised date**：2007－07－21

Foundation item：The Korea Institute of Construction and Transportation Technology Evaluation and Planning under the Ministry of Construction and Transportation in Korea(05－D10)

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摘要：高水压、大渗流量的海底隧道而言，为防止涌水的事故发生，设计一高效的排水系统是非常重要的。大多数海底隧道的崩溃都和高水压、大渗流量有着密切联系。为了寻求其中的规律，研究了一系列的 TBM 和 NATM 隧道案例。案例研究结果表明，如果在隧道挖掘前能够预测渗流量以及预先设置排水系统就能有效预防工程事故。据此，提出了新水平预排水系统。通过数值模拟计算，分析了在海底隧道的施工期，从隧道工作面通过排水孔泄水的效果。假设海底隧道的岩层覆盖层厚 100 m，水深 60 m，并假设设置水平预排水系统之后的地层渗透系数为 0.003 6 m/h。计算结果表明，隧道顶点总水头减少了 60%，隧道拱脚线总水头减少了 53%。当排水管直径为 5 cm、地层渗透系数为 0.003 6 m/h 时，为增强排水效果，排水管的长度不得超过 250 m。数值分析及排水效果均表明，所提出的水平预排水系统能及时排水并减小水压力。在海底隧道建设方面，这个系统可为其提出一种新的解决方案。
关键词：海底隧道；排水系统；涌水；水平向钻孔；漏水

1　INTRODUCTION

Numerous collapses in subsea tunnels are associated with huge inrushes of water due to high water heads and inflows through high permeability zones. Most water inflows during construction originate from very limited areas of the tunnel. However，these leakages are difficult to predict，largely because it is hard to：(1) characterize the geological conditions；(2) represent the site permeability with the tested results，and (3) reflect the site conditions in prediction methods[1]. Due to practical difficulties and high costs，site investigations are limited and geological conditions are commonly unforeseen in subsea tunnels. However，sudden leakages during tunnelling can lead to tunnel collapse and flooding. The saline constituent of leakage water could in turn damage the performance of tunnelling equipment and support materials[2]. Leakage areas，which clearly have adverse effects on the tunnel stability，should thus be controlled to minimize these risks.

The present study is a part of a research project (Development of Water Control Technology in Undersea Structures) for subsea tunnels in Korea. This paper suggests an effective pre-drainage system at a limited leakage area with a high water head and huge inflows during the construction stage. This system is not a means of setting the risks but a preventive countermeasure. In order to determine the causes of and countermeasures for flooding cases，a dozen of tunnelling cases are studied. Numerical analyses are performed to analyze the application of horizontal pre-drainage holes as a water head controlling effect on the tunnel face during the construction of subsea tunnels. Drainage performance of the drainage hole is also analyzed.

2　CASE STUDY

A total of nine flooding cases including two subsea tunnels during construction stages are analyzed，as shown in Table 1[3]. The case study shows that the major cause of tunnel collapses was an unforeseen high permeability zone with a high water head. The flooding was considerable enough to induce a total loss of the tunnel(see Fig.1)[4] or severe damage to the tunnel structure and delays in the construction schedule. As a countermeasure against the flooding，drainage pipes were placed in the tunnel faces to drain leakage water. Grouting and/or cofferdams were adopted to maintain the tunnel stability. Therefore，the case study demonstrates that if the leakage had been forecasted and the tunnel had been pre-drained prior to excavation，the leakage could have been prevented. In order to minimize such risk，probe drilling and pre-grouting[5] are frequently used in subsea tunnel construction[6]. However，probe drilling has a negative impact on the tunnelling schedule due to drilling and drainage time[7].

3　STEADY-STATE FLOW MODEL AND DRAIN PERFORMANCE

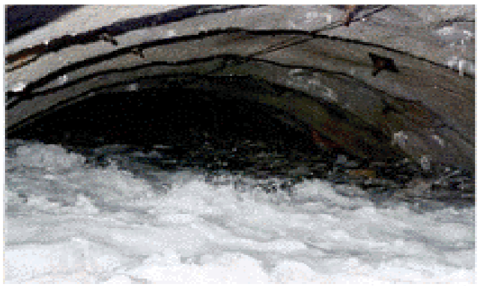
R. E. Goodman et al.[8] suggested a theoretical model for the volume of seepage water into a tunnel in isotropic homogeneous ground. The equation requires

Table 1 Flooding cases in tunnelling[3]

Excavation method	Ground condition	Tunnel	Causes and results	Countermeasures
Shield TBM	Weak layer，complex geology	Great Belt，Denmark(Subsea)	(1) Cause：high water head(maximum 66 m). (2) Maximum water inflow：3－8 m^3/s. (3) Malfunction of two TBMs. (4) Schedule delay 2 years，cost rising 50 %	Protective cofferdam：30
Open TBM/ drill and blast	Complex tectonic hydro-geological condition	Severo-Muysky，Russia	1. Causes： (1) Unforeseen local watered system of fracture，water head＞2 MPa. 2. Disturbance of the chemical stabilization zone. (1) 1979－water inrush：700 m^3/h. (2) 197909－198003： water inrush：350 m^3/h. (3) 1981－water inflow：5－70 m^3/h. (4)198704－maximum water inrush：4 000 m^3/h. (5) 198904 － water inrush： 700 m^3/h，inundation length：900 m	Pumping out the water，monitoring，install concrete coffer-dam
Drill and blast	Fractured limestone(115 m high，30 m wide fault zone)	Grand Sasso，Italia	(1) Cause：low water permeability of fault gouge contributed to high water pressure. (2) Inrush of water：36 000 m^3. (3) Schedule delay，cost rising	(1) Emergency work：concrete coffer-dam，grouting，drainage hole (2) Reinforcement：drainage well：26 km；reconstruction：1.6 km；silica gel grouting：9 430 t
Drill and blast	Sediment rock，andesite，tuff	Seikan，Japan	(1) Cause：high water pressure(maximum 240 m). (2) 1976－water inrush：70 m^3/min totally inundation of tunnel. (3) 4 times water inflows	Waterproof dam，pre-grouting，coffer-dam，by pass adit
Drill and blast	Igneous rock	Sinvada，Japan	(1) Cause：grouting failure. (2) Water inrush：7 000 m^3，sand inrush：1 500 m^3. (3) Schedule delay about 4.5 months	Well point drainage：150 dm^3/d，45 d；60 dm^3/d，3 months
Drill and blast	Tuff，breccia	Nakayama，Japan	(1) Cause：high water pressure(2 MPa). (2) Water inrush：100 m^3/h	By pass adit，grouting
Drill and blast	－	Anray，Japan	(1) Water inflow：0.02 m^3/min. (2) Inundation：1.5 km	Two drainage adits
Drill and blast	Limestone，dolomite	Bosruk，Austria	(1) Cause：fracture zone. (2) Water inrush：1.1 m^3/s	Drainage adit：drainage time 7 months
Drill and blast	Very complex geology	New Yungchuen，Taiwan	(1) Causes：high water pressure(5 MPa). (2) Fracture zone and gouge. (3) 1st water inrush：25 m^3/min，2nd water inrush：80 m^3/min，3rd debris inrush：more than 15 000 m^3. (4) Buried 540 m of tunnel	(1) Drainage hole(ϕ 100 mm)：26 holes，80－130 m length；62 holes：12－30 m length. (2) Drainage tunnel：1 067 m (3) Grouting

(a) After 1 hour：25 m^3/min

(b) After 3 days：80 m^3/min



(c) After 13 days：15 000 m^3/min

Fig.1 Process of flooding in New Yungchuen tunnel[4]

the equivalent coefficient of permeability for the isotropic homogeneous ground and the equivalent radius of the tunnel. The volume of drained water is proportional to the permeability of the ground and the water depth. However，the rock cover has an inverse relationship with the volume of drained water. As shown in Fig.2，the equation can be used for evaluating the volume of drained water that flows into the drainage hole. Thus it can be written as：

$$Q = 2\pi k \frac{H+h}{\ln\left(\frac{2h}{R}\right)} \tag{1}$$

where Q is the volume of the drained water，k is the coefficient of permeability，R is the equivalent radius of the drain，H is the water depth，and h is the rock cover.

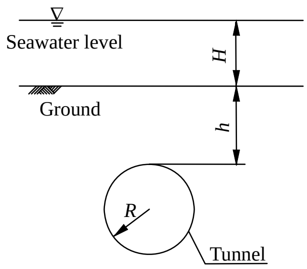


Fig.2 Tunnel under seabed

The flow of an incompressible ideal fluid can be characterized by the Bernoulli equation. The flow in a drainage pipe is assumed to be an ideal fluid flow. However，there is an energy loss from the movement of the fluid in the drainage pipe due to friction between the moving fluid and the surface of the drainage pipe. Generally，the Hazen-Williams equation is used for considering the friction in a pipe flow. The Hazen-Williams equation for mean velocity V is given as：

$$V = 0.849 C_{\mathrm{HW}} R_{\mathrm{h}}^{0.63} S^{0.54} \tag{2}$$

where C_{HW} is the Hazen-Williams roughness constant，R_{h} is the hydraulic radius of the drainage pipe(m)，and S is the hydraulic gradient of the flow(m/m). C_{HW} is an empirical value，and typical C_{HW} factors used in design are shown in Table 2. In a very rough pipe，it can be assumed as $C_{\mathrm{HW}} = 80$.

Table 2 Typical Hazen-Williams coefficient(C_{HW})

Material	C_{HW}
Asbestos cement	140
Brass	130－140
Brick sewer	90－100
Cast-Iron 10 years old	107－113
Cast-Iron 20 years old	89－100
Cast-Iron 30 years old	75－90
Cast-Iron 40 years old	64－83
Concrete	100－140
Copper or brass	130－140
Corrugated metal	60
Fiber	140
Fiber glass pipe—FRP	150
Galvanized iron	120
Glass	130
Lead	130－140

4 ANALYSIS OF THE DRAINAGE SYSTEM

4.1 Seepage analysis for the drainage system

Fig.3 shows the concept of the proposed water drainage system using horizontal pre-drainage holes and the analysis conditions. In order to provide a sufficient drainage effect，it is supposed that the drainage holes are installed with HDD(horizontal directional drilling) several months prior to the tunnel excavation. HDD is a relatively new drilling method，and mainly used in telecommunication industry in North America[9]. However，this method is an efficient and cost-effective method[10] to investigate ground condition，especially in subsea ground[11].

Eq.(1) provides the volume of seepage water into a drain for the ideal simple model. Therefore，numerical analysis is required for more complicate condition. Numerical analyses are performed to analyze the water head controlling effect at the tunnel

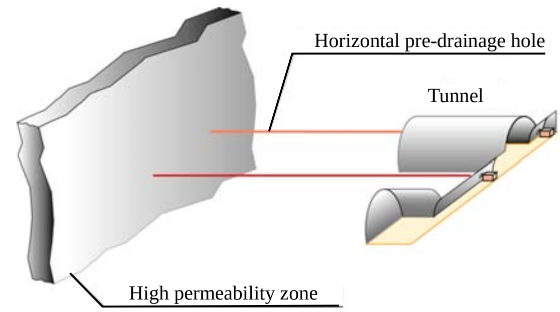
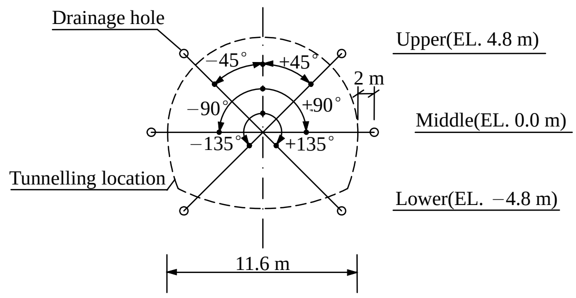


Fig.3　Concept of the water drainage system

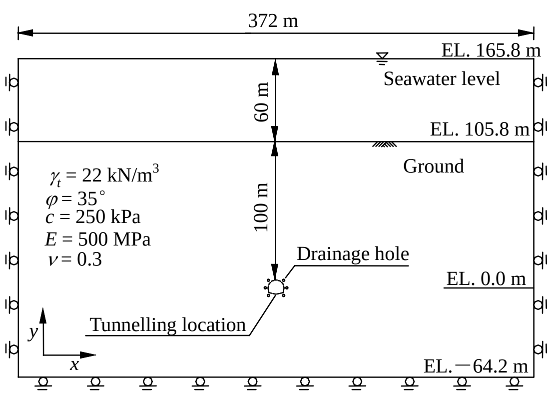


(b) Drainage location

Fig.4　Analysis conditions and drainage location

face location and the volume of drained water from drainage holes during tunnelling.

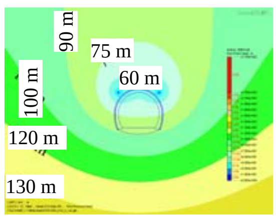
Analysis conditions and drainage locations are shown in Fig.4. In Fig.4(a)，considering the design case of the Seikan tunnel，which has 100 m of rock cover depth to avoid unstable ground conditions，it is supposed that the rock cover of the analyzed subsea tunnel is 100 m. The maximum depth of seawater is assumed to be 60 m，which is the average depth of the seawater in the southern part of the Korean Peninsula. Two boreholes are installed 2 m outside of the predicted tunnelling surface with four different radii(2.5，5.0，7.5，10.0 cm，respectively). As shown in Fig.4(b)，the directions of the drainage holes are the upper(±45° direction from the tunnel center line)，the middle(±90° direction from the tunnel center line)，the lower(±135° direction from the tunnel center line) regions of the tunnel as well as all sides(upper，middle，and lower). Five different cases of ground permeability，i.e. 3.6×10^{-2}，3.6×10^{-3}，3.6×10^{-4}，3.6×10^{-6}，and 3.6×10^{-8} m^3/h，are used in the analysis. The material properties are given in Fig.4(a). It is also supposed that there is no change of the seawater level from the drainage for there is a sufficient supply of



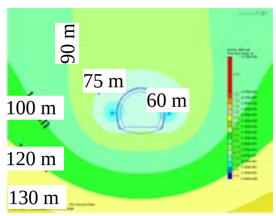
(a) Analytical condition

seawater. Two-dimensional steady state flow analyses are performed with MIDAS commercial code.

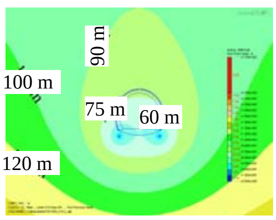
The effects of the location and radius of the drainage hole for the water pressure reduction at the crown and the spring line are analyzed as shown in Figs.5－7. The results show that the optimal locations of the drainage holes to reduce the water pressure are on all sides as shown in Fig.5(d) and Fig.6. However，this requires a larger number of drainage holes(6 holes) than other cases. One of the most important zones in tunnelling is the right upper side of the tunnel with the crown. The most effective and economical location is thus the upper side of the tunnel.



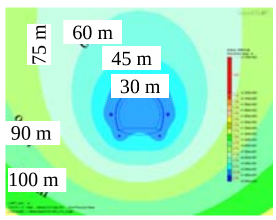
(a) Upper side



(b) Middle side



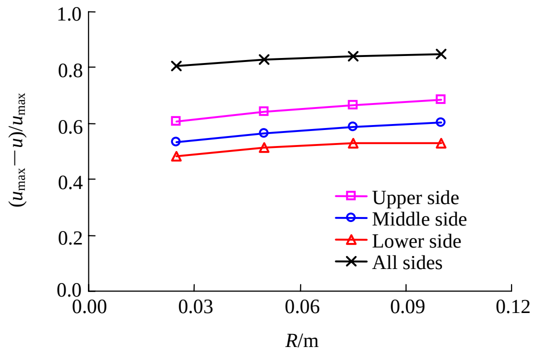
(c) Lower side



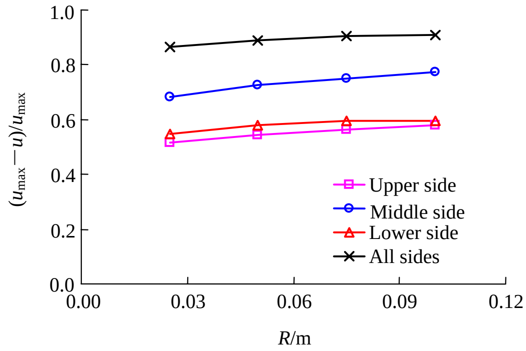
(d) All sides

Fig.5　Pressure head change with drain location(R = 10 cm，k = 0.003 6 m/h)

As shown in Fig.6，the location of the drainage hole is more important with respect to the water pressure reduction effect than is the radius of the drainage hole. Fig.7 shows the pressure head change with the drain radius for the upper side drainage，

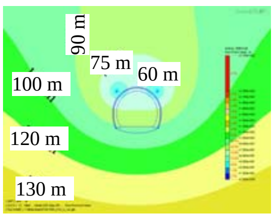


(a) Crown

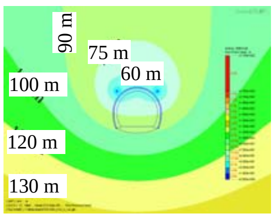


(b) Spring line

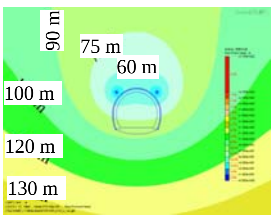
Fig.6　Effect of the drain location and radius for water pressure reduction



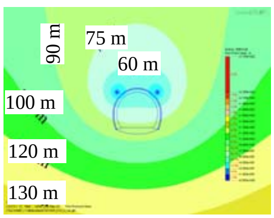
(a) R = 2.5 cm



(b) R = 5.0 cm



(c) R = 7.5 cm

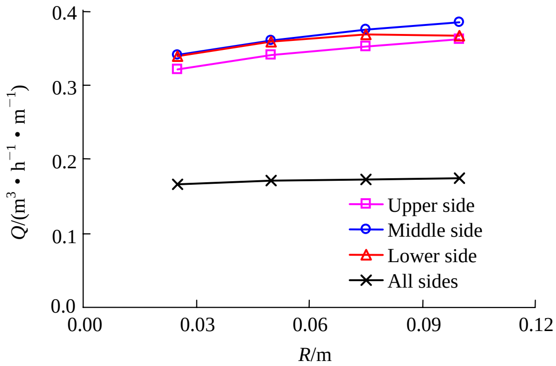


(d) R = 10 cm

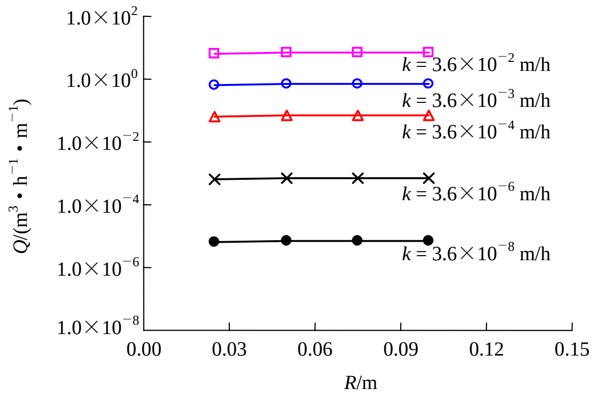
Fig.7　Pressure head change with the drain radius(upper side drainage，k = 0.003 6 m/h)

where u is the reduced water pressure due to the drainage system and u_{max} is the hydrostatic pressure before installation of the drainage system. When the permeability of the ground is 0.003 6 m/h，the water pressure is reduced by about 60% at the tunnel crown and 53% at the tunnel spring line(see Fig.6).

The volume of the drainage water with different drain locations and the radius is presented in Fig.8(a). The result shows that there is little change in the volume with the drain location，and a small increase of the volume with an increase of the radius. Fig.8(b) shows that the volume of the drainage water significantly increases with an increase of the ground permeability. However，the effect of the drainage radius is relatively small.



(a) Drainage location



(b) Permeability

Fig.8　Effect of the drain radii on volume of the drained water with drain location and permeability

4.2　Maximum length of the drainage pipe

The efficiency of a drainage pipe depends on the radii of the pipe，slope，and energy loss，which depend on the length and the wall friction. If the energy loss and/or volume of the inflow water to the pipe are sufficiently large，then the pressure in the pipe will be equal to the water pressure of the outer ground. The efficiency of the drainage system and the effect of the water pressure reduction will be significantly decreased. This study analyzes the relationship between the radius and the length of the drainage pipe in given ground permeability. To simplify the problem，it is assumed that the slope of the drainage pipe is 1%. The code used for the analysis is EPANET(Ver. 2.0)，which was developed by the U.S. Environmental Protection Agency. The Hazen-Williams roughness constant C_{HW} is conservatively assumed as $C_{HW} = 80$.

The analytical results are shown in Fig.9. The Q_{max}(maximum outflow) is the volume of the drainage water when the water pressure in the pipe is equal to the water pressure of the ground. The cumulative inflow is the cumulative inflow，which is proportional to the width of the high permeability zone under the radius of the drainage pipe，which is 5 cm. As shown in Fig.9，magnitude of Q_{max} decreases with the length of the pipe. This trend is more evident for larger pipes. The required scale and length of the pipe for effective drainage are significantly changed by the ground permeability. As shown in Fig.9，when k is 0.003 6 m/h，the length of the pipe should not exceed 250 m. However，if k is 0.036 m/h，the length of the pipe should be less than 50 m.

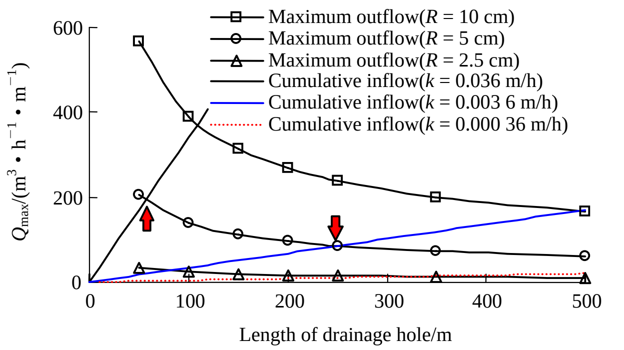


Fig.9　Maximum outflow vs. length of the drainage pipe

5　CONCLUSIONS

It can be concluded that the suggested horizontal pre-drainage system delivers an evident drainage and water head reducing effect，and is an effective water controlling method for subsea tunnels. This system will provide an effective pre-drainage system at limited leakage areas with a high water head and huge inflows during the construction stage. In the given conditions，this system reduced the water pressure by roughly 60% at the tunnel crown and 53% at the tunnel spring line. The radius and length of the drainage hole should be determined by the ground permeability. For practical purposes，the radius of the drainage hole should be 5 cm，because of the drilling bit size of HDD. Therefore，to maintain the efficiency of the drainage system，it is necessary to increase the number of drilling holes，or reduce the drainage length.

References(参考文献):

[1] RAYMER J H. Predicting groundwater inflow into hard rock tunnels[C]// Construction and Geology of the Massachusetts Water Resources Authority Tunnel. Eastern Massachusetts：[s. n.]，2001：50－53.

[2] NILSEN B，PALMSTRØM A. Stability and water leakage of hard rock subsea tunnels[C]// Modern Tunnelling Science and Technology. Kyoto：[s. n.]，2001：497－502.

[3] WANG T T，WANG W L，LIN M L. Harnessing the catastrophic inrush of water into New Yungchuen tunnel in Taiwan[C]// Proceedings of ITA-AITES World Tunnel Congress and the 30th ITA General Assembly. Singapore：Torus Press Ltd.，2004：418－426.

[4] VLASOV S N，MAKOVSKY L V，MERKIN V E. Accidents in transportation and subway tunnels[M]. Moscow：Elex-KM Publishers，Ltd.，2000.

[5] CESANO D，OLOFSSON B，BAGTZOGLOU A C. Parameters regulating groundwater inflows into hardrock tunnels—a statistical study of the Bolmen tunnel in southern Sweden[J]. Tunnels and Underground Space Technology，2000，15(2)：153－165.

[6] GRØV E，BLINDHEIM O T. Risks in adjustable fixed prices contracts[J]. Tunnels and Tunnelling International，2003，35(6)：45－47.

[7] Question about the Eiksundtunnelen[OL]. http：//sveinskeide.net/eiksundtunnelen/engelsk/engelsk.htm，2007.

[8] GOODMAN R E，MOYE D G，SCHALKWYK A，et al. Groundwater inflows during tunnel driving[J]. Engineering Geology，1965，2(1)：39－56.

[9] BAIK H S，ABRAHAM D M，GOKHALE S. A decision support system for horizontal directional drilling[J]. Tunnels and Underground Space Technology，2003，18(1)：99－109.

[10] ALLOUCHE E N，ARIARATNAM S T，BIGGAR K W，et al. Horizontal sampling：a new direction in site characterization[J]. Tunneling and Underground Space Technology，1997，12(Supp.1)：17－25.

[11] GAHIR J，RADWANSKI R，HAFEZ T A. Design and construction challenges of sub-sea directional drilled crossings on the Palm Jumeriah，Dubai[J]. Tunnels and Underground Space Technology，2006，21(3/4)：251.