MIDAS SQUARE

MIDAS SQUARE 공학 기술강연

Hydraulic and Hydrological Considerations in the Design of Underground Structures

지하구조물 설계의 수리 · 수문학적 고찰

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1. Introduction

1. Introduction

Recent Issues of Climate Change and the Underground Structures

2023. 07. 15

Flooding of
Underpass
Korea
14 Dead

2023. 07. 20

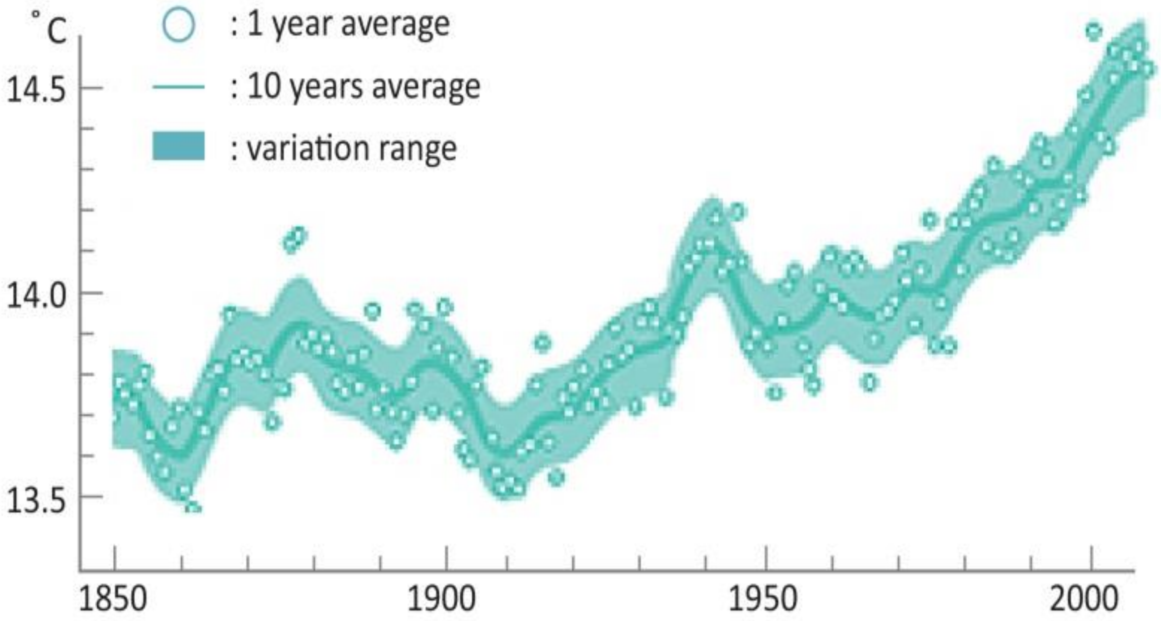
Flooding of
Jeong Jou Metro,
China

25 Dead

1. Introduction

Climate change

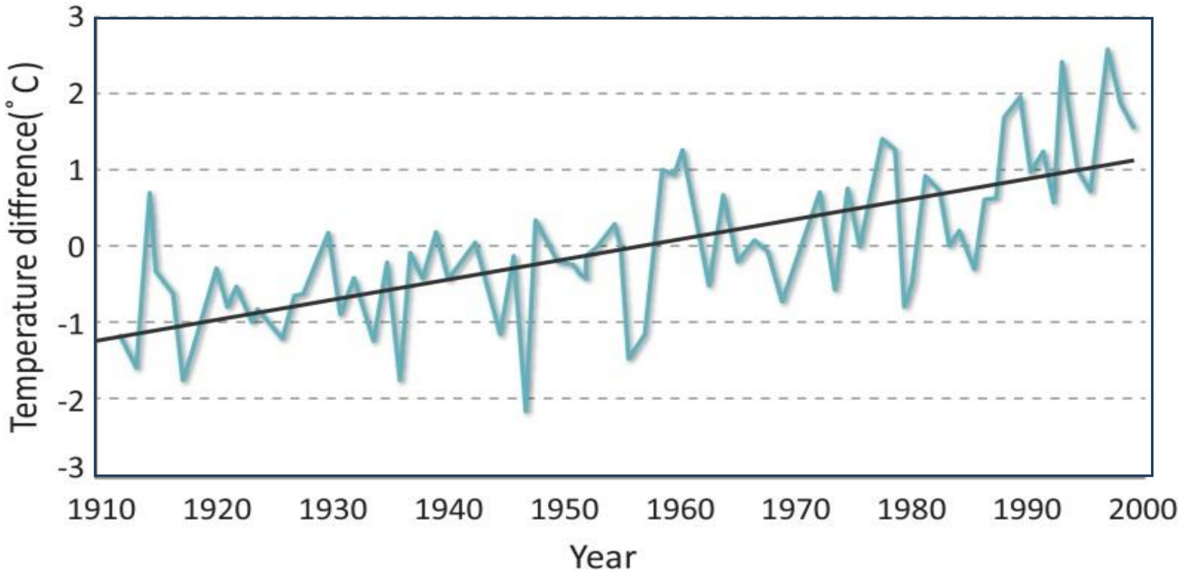
World Temperature Change

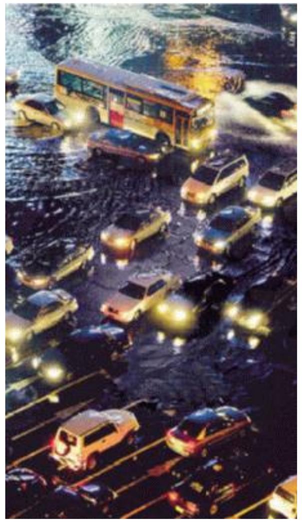


- 0.74 °C ↑ over the last 100 yrs
- 6.40 °C ↑ at the end of this century

Climate change has caused flood, drought, heat wave and destruction of ecosystem.

Temperature Change in Korea





- 1.7 °C ↑ over the last 100 years
- Annual rainfall is 1,245mm, 70% of annual rain in the short rainy season from July to October

The effects of global warming on the Korean Peninsula have been intensified.

Water is a Central Issue
in Climate Change

Climate change is felt through water

by causing drought, flood, sea level rise and destruction of ecosystem

Fundamentally, global efforts to reduce greenhouse gas emission is needed.

Securing of infra systems to control water is also required.

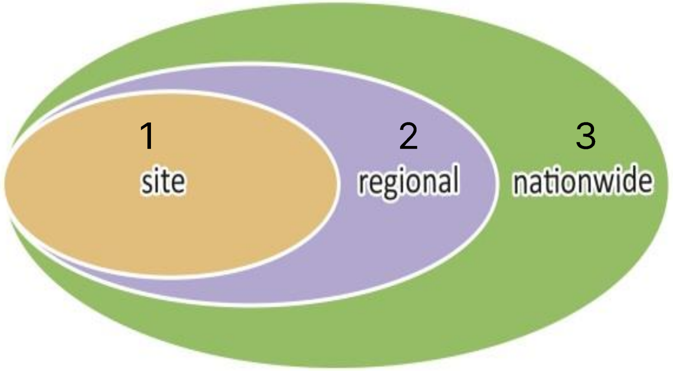
Green Infrastructure

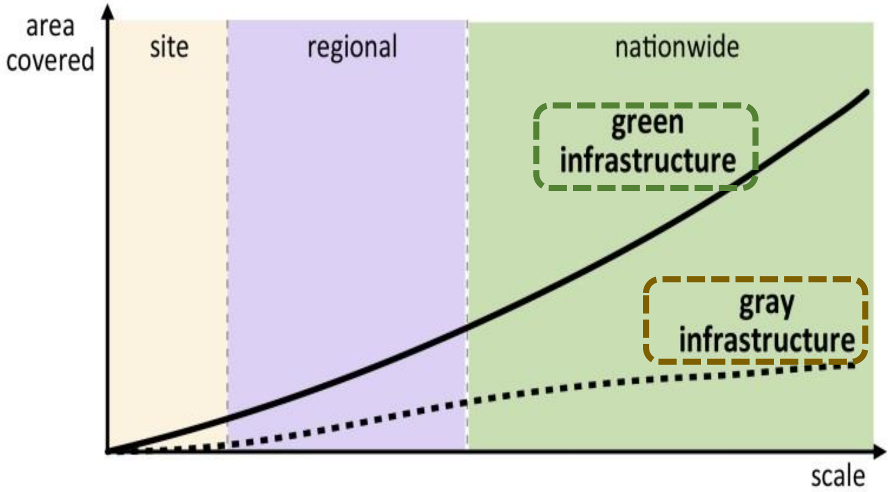
General trends

Mountain Reforestation & River Restoration

- control flood & drought
- recover ecosystem
- improve water quality
- secure water resource

- **green Infrastructure: the space planned as a natural part of nature**





1. the storm water management systems
2. the patchwork of natural areas
3. the integrated water resource management

※ grey infrastructure: concrete oriented structure

1. Introduction

2023.09.20
조선일보 A38면 오피니언

토목 혐오증의 좁은 생각

한삼희의 환경칼럼

선임논설위원

작년 포항 참변, 강남 침수
'토목 기피'에서 비롯
미호강도 준설했다면
오송 참사 피했을 것
청정 안양천은 토목의 성과
관념 환경주의 탈출해야

작년 9월 태풍 힌남노 때 포항 냉천이 범람해 아파트 지하주차장 침수로 7명이 목숨을 잃었다. 포항제철소도 물에 잠겨 수천억원 피해를 봤다. 당시 냉천 상류에 항사댐이 있었더라면 범람을 피할 수 있지 않았겠냐는 지적들이 있었다. 포항시는 10여 년 전부터 저수량 476만t의 중소 규모 항사댐 건설을 정부에 건의해왔다. 2016년 국토교통부의 '댐 희망지 신청제' 시행 때는 주민 동의를 받아 정부에 신청했다. 하지만 2017년 환경 단체들이 댐 입지 부근에 활성단층이 지나고 있다며 반대해 성사되지 않았다. 항사댐 건설이 추진됐더라도 작년 9월 시점까지 준공이 됐을지는 알 수 없다. 항사댐이 완공됐다면 힌남노 폭우에 버틸 수 있었던 것인지도 속단할 수는 없다. 그러나 확실히 더 안전해지기는 했을 것이다.

항사댐 건설을 포기한 문재인 정부는 아예 신규 댐 건설 중단을 선언했다. 환경운동가 출신이 장관이었던 환경부는 2018년 9월 '지속가능한 물관리'란 정책 청사진을 발표했다. 2012년의 댐건설 장기계획에 반영돼 있던 14개 댐 가운데 추진 중이던 2곳을 제외하고 12곳은 건설을 포기한다고 했다. 해수 담수화도 안 하겠다고 했다. 터무니없는 토목 기피, 과학기술 혐오였다.

작년 8월 극한 폭우로 빚어진 서울 강남 수해도 시민운동가 출신 서울시장이 대심도 빗물터널 건설을 백지화하지 않았다면 피해가 훨씬 줄었을 것이다. 빗물터널은 2011년 오세훈 당시 시장이 서울 7곳에 짓겠다고 발표했었다. 그러나 후임 시장은 진행 중이던 양천구 외의 6곳은 없던 일로 만들었다. 상습 수몰 지역이던 양천구 신월동 일대는 2020년 빗물터널이 완공되면서 작년 수해 때 거의 피해를 입지 않았다.

14명 사망자를 낸 지난 7월의 청주시 오송읍 지하차도 침수 참사도 미호강 준설이 이뤄졌더라면 피할 수 있었을 것이다. 오송 재난을 겪고 나서 환경부는 지난달 말 국가하천 19곳에서 바닥을 파내는 준설 등 하천 정비에 나서겠다는 계획을 밝혔다. 10개 댐 신설 구상도 내놨다. 정권이 교체된 후에야 댐 건설이 '백지화'에서 '재개'로 돌아섰다.

문재인 정부의 하천 정책 기조는 '자연대로 내버려두라'는 것이었다. 금강·영산강 3개 보 해체도 이른바 '재(再)자연화'라는 것이다. 자연에 손을 대 가공하는 것에 질색을 한다. 준설도 하천 생물의 서식처를 교란하는 것이니 자제하자는 것이다. 탈원전도 같은 흐름이다. 과학기술의 집약체이자 거대 인프라 결집체인 원자력발전을 포기하고 자연의 햇빛과 바람 에너지로 대신하자는 것이다.

토목과 과학기술에의 혐오와 적대시는 '관념 환경주의'의 좁은 시각이다. 토목 그 자체가 반환경적이고, 과학기술이 비도덕적인 것이 아니다. 나쁜 토목이 있다면, 좋은 토목도 있다. 과학기술도 그 본질이 친환경이거나 반환경인 것은 아니다. 과학기술과 토목은 때로 환경을 해칠 수도 있지만, 자연과 환경을 보전하기 위해선 꼭 필요한 핵심 수단이다.

안양천의 경우 1980년대 중반 오염도(BOD)가 200을 넘나들던 시궁창 하천이었다. 백지를 물속 5㎝ 깊이만 넣어도 보이지 않았을 것이다. 그 안양천의 최근 오염도가 2~5 수준이다. 전적으로 과학기술과 토목의 힘이었다. 유역 하수관망을 깔고 정화처리수는 다시 상류로 끌어올려 유량(流量)을 유지시켰다. 하수처리장은 지하로 넣었고 지상엔 공원을 만들었다. 그 덕분에 수십만, 수백만 유역 인구가 산책로를 낀 맑은 샛강의 혜택을 입고 있다. 서울 청계천도 다르지 않다.

손대지 않은 자연에서 영감과 생기를 얻는 것이 사실이다. 그러나 사람의 자연 의존성이 커질수록 환경은 더 파괴되는 수가 많다. 한국의 산이 울창하게 된 것은 나무를 열심히 심었기 때문이기도 하지만, 석탄·석유·전기 등 다른 풍부한 에너지를 활용하면서 더 이상 땔감 나무가 필요 없게 된 탓도 크다. 농약과 비료, 트랙터로 작은 농지에서 풍족한 식량을 생산하면서 숲을 베어내 논밭으로 바꿀 이유도 없어졌다. 원자력발전소는 초(超)고밀도 에너지를 공급해준다. 좁은 국토를 가진 한국으로선 무엇보다 친환경 에너지다.

많은 사람이 자연과 어우러지며 사는 것을 동경한다. 그렇지만 자연은 늘 조화롭고 평화로운 것만은 아니다. 폭풍, 지진, 질병, 홍수 등이 모두 자연에서 비롯되는 것들이다. 토목과 과학기술은 그것들을 교정해 더 안전하고 더 자연과 조화를 이루며 살기 위해 필요한 수단이다. 발전이란 인간 적대적 자연환경을 인간 친화적으로 바꿔놓는 과정이다. 댐 건설 포기, 하천 준설 반대는 복잡한 현실을 너무 단순하게 규격화해 바라보는 오도(誤導)된 토목 기피증, 토목 혐오증이다. 과학기술과 토목에 도덕의 굴레를 덮어씌워 배척할 이유가 없다. 그건 관념 환경주의라는 '생각의 감옥'에 스스로를 가두는 것이다.

"Gray infrastructure" can effectively support "Green infrastructure ".

1. Introduction

2023.09.20 Wendsday
Choseon Daily News, A38 Opinion

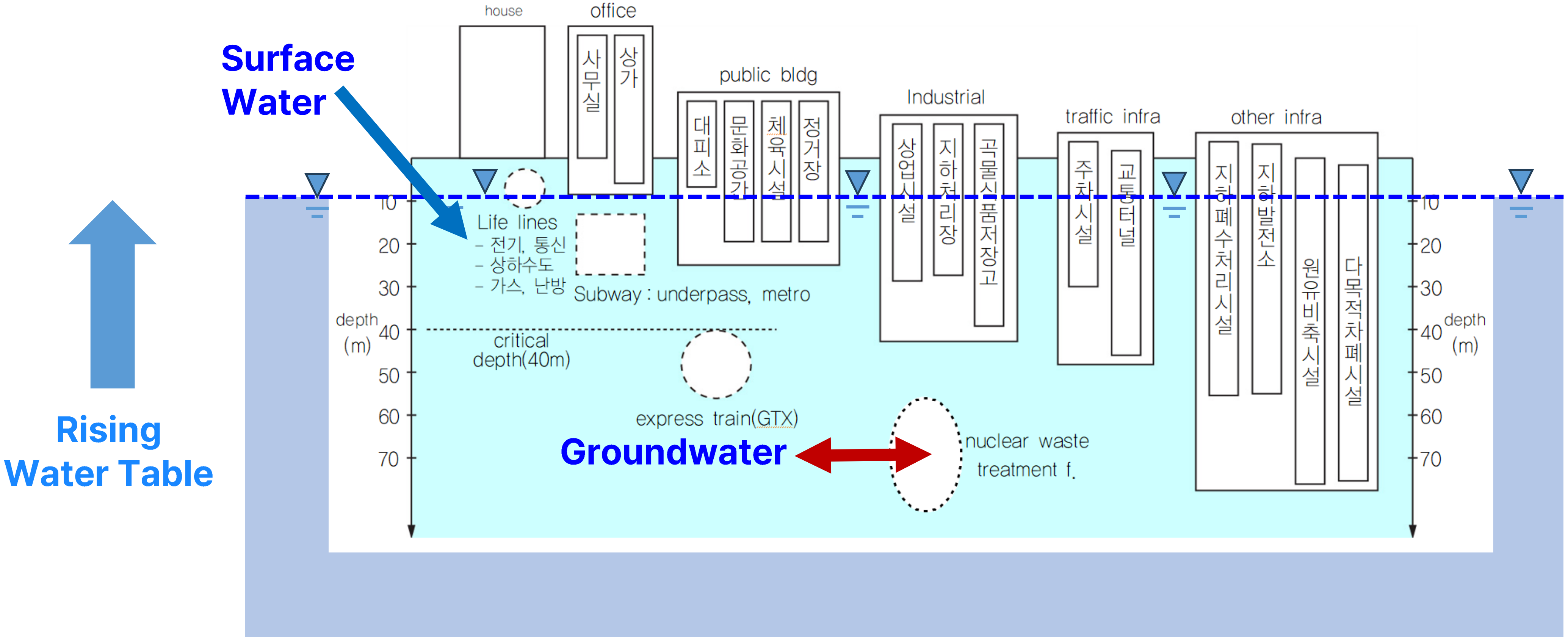
……… .

Drawing inspiration and vitality from untouched nature is undoubtedly true. However, as our reliance on nature increases, the environment often bears the brunt of it. The lushness of Korea's mountains owes partly to diligent tree planting, but it's also because we no longer require firewood, thanks to the abundant resources like coal, oil, and electricity we now utilize. There's no longer a need to clear forests and transform them into fields on small farms, given our capacity to produce bountiful crops with pesticides, fertilizers, and tractors. Nuclear power plants offer a source of super-dense energy for a country with limited land, making them a highly eco-friendly choice.

While many aspire to live in harmony with nature, it's important to acknowledge that nature isn't always tranquil and harmonious. Storms, earthquakes, diseases, floods, and more are all natural occurrences. Civil engineering and advancements in science and technology serve as means to mitigate these challenges, creating a safer and more harmonious coexistence with nature. Development involves the process of transforming an environment that can be adversarial into one that is more hospitable to humanity. Abandoning dam construction and opposing river dredging are rooted in misguided aversions to civil engineering, often resulting from an oversimplification of complex realities and an unjustified dislike for civil engineering. There's no valid reason to impose moral constraints on science, technology, and civil engineering, as this would be akin to confining oneself within the "prison of conceptual environmentalism."

Climate Change and Vulnerability of the Underground Structures

Hydraulic and Hydrological Risks



Surface Water

Rising Water Table

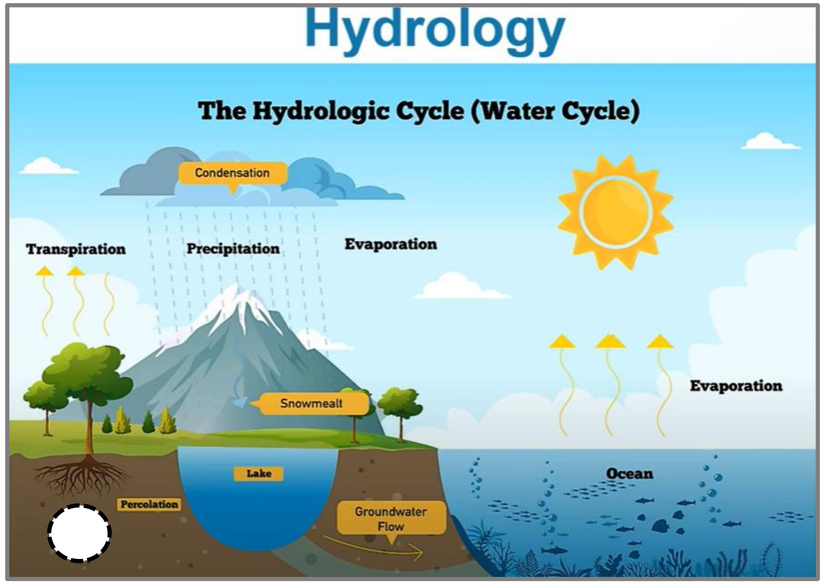
Groundwater

2. Hydraulic and Hydrological Significance in the Design of Underground Structures

지하구조물 설계의 수리·수문학적 중요성

2.1

Water Balance and Underground Structures

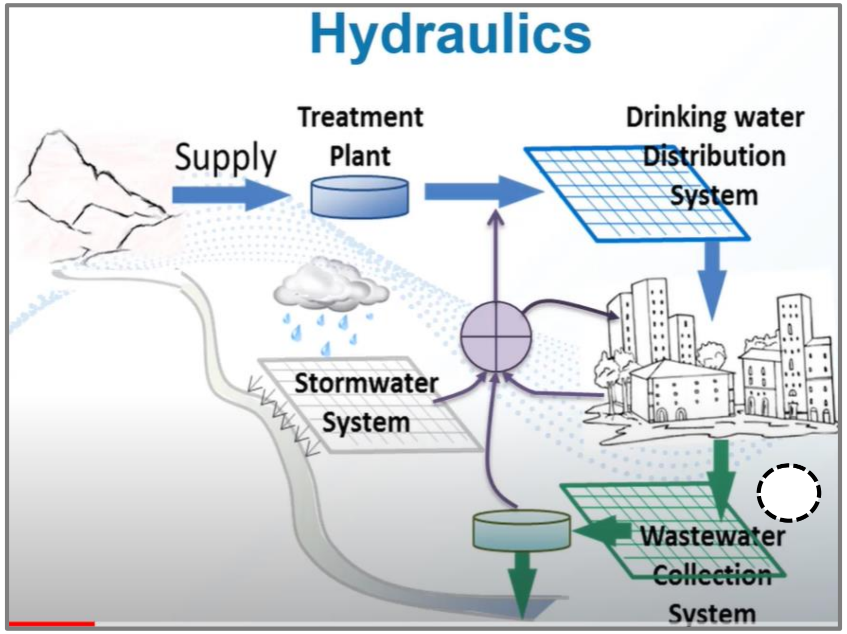


Hydrology - The study or science of transforming rainfall amount into quantity of runoff.

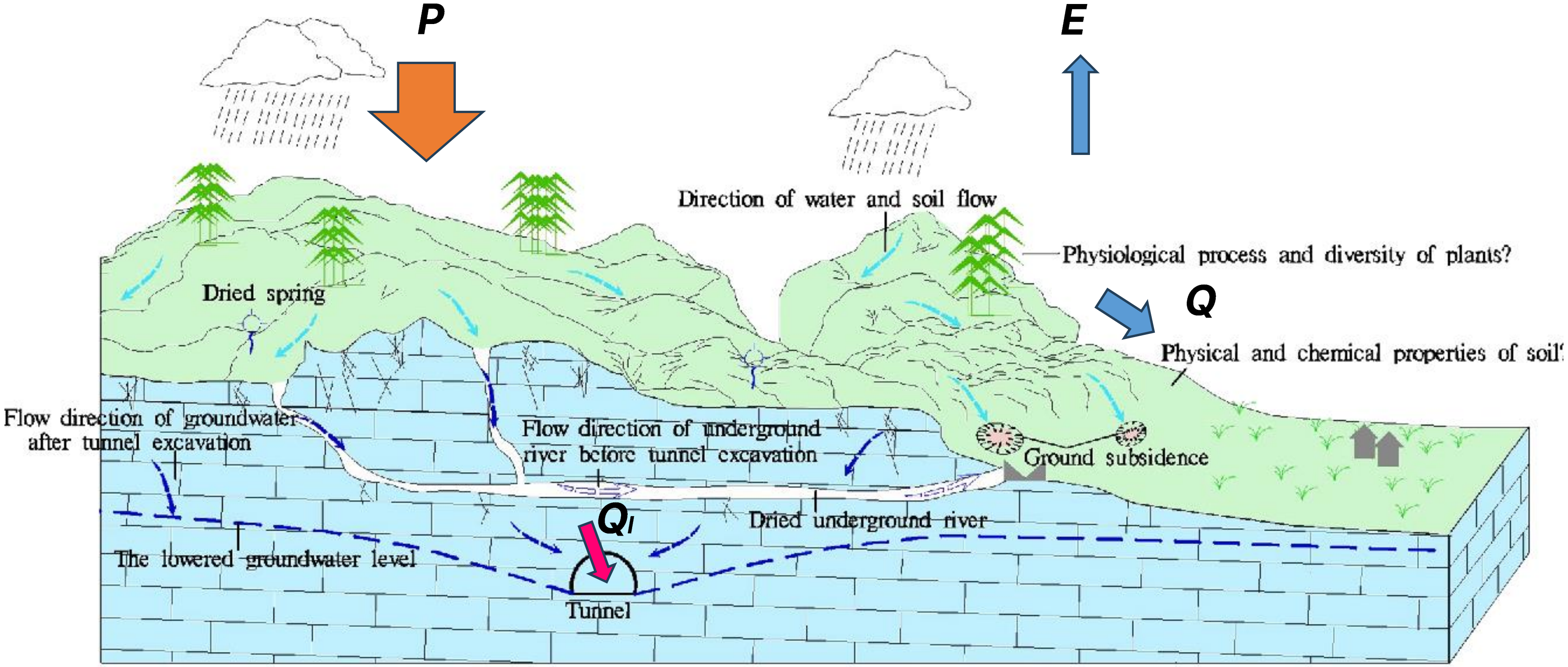
Effect of Surface Water on the Underground Structures

Hydraulics – The study or science of the motion of liquids in relation to disciplines such as fluid mechanics and fluid dynamics.

Effect of Groundwater on the Underground Structures



Effect of Underground Construction on the Water Balance

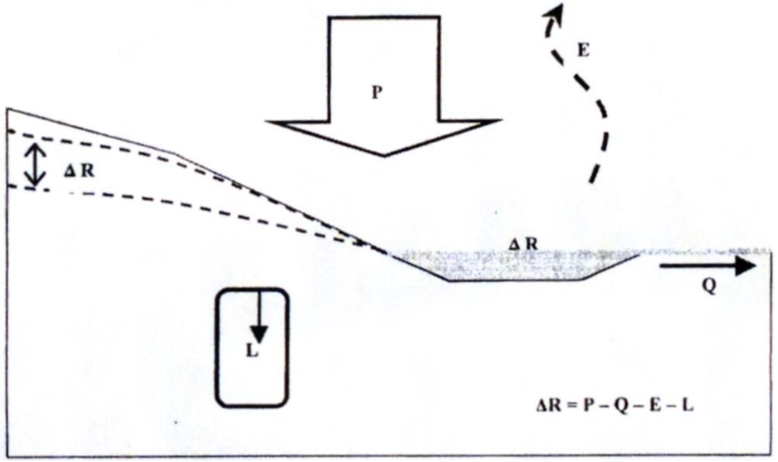


Underground Structure and Water Balance

- **Water Balance for long period**

$$P = Q + E$$

P : precipitation
Q : run off
E : evapotranspiration



(Ref: NGI Pb #12)

- **Water Balance for short period**

$$P = Q + E + \Delta R$$

ΔR : difference in groundwater and surface water storage for a given period

2.2
Hydraulic and Hydrological Significance

Hydraulic Aspects

Impact of leakage on Water Balance

For a given catchment area, leakage Q_l occurs

$$\Delta R = P - (Q + E + Q_l)$$

Leakage Characteristics

$$Q_l = f(k, \ldots)$$

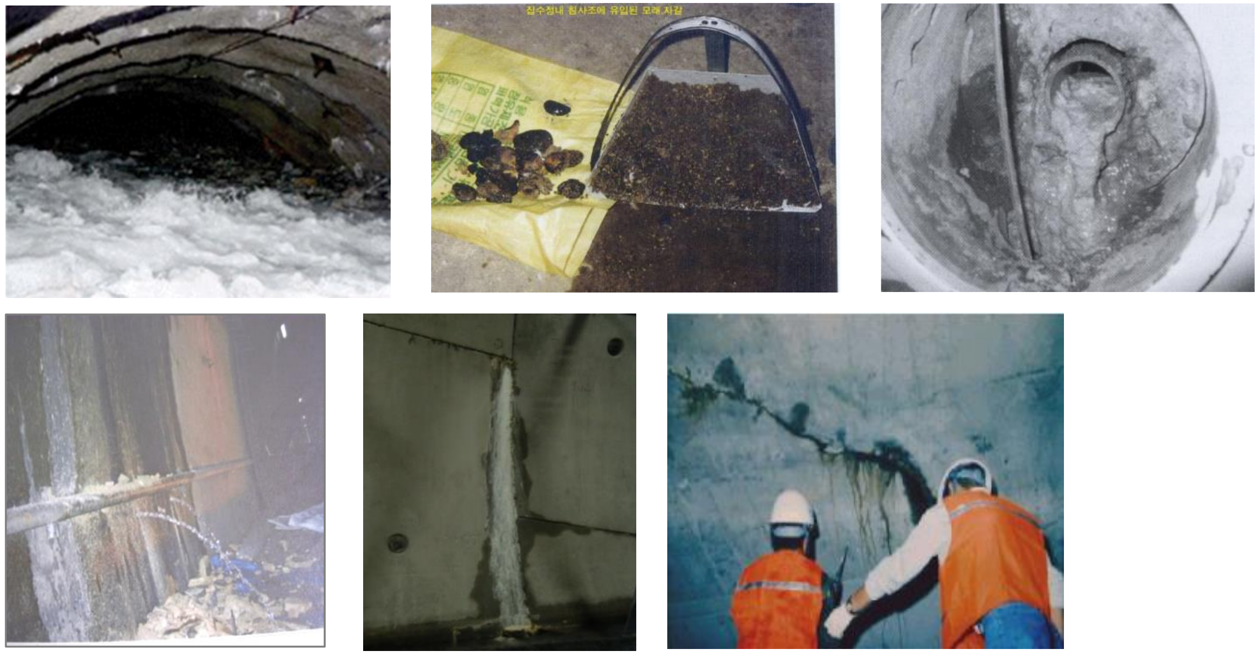
***k* : ground permeability**

Leakage control causes water pressure on the Structure
: P-Q Interaction

Groundwater ➡ Hydraulic Aspects
Hydraulic Environmental Aspects
Site/Structural Problems

Problems Caused by the Groundwater

- **Leakage(and soil erosion)**



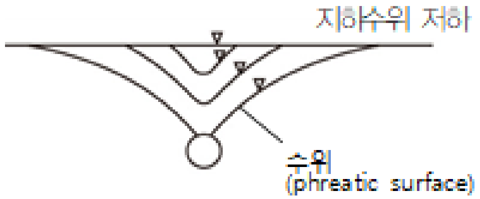
- **Water Pressure on the Structures**

Leakage Problems

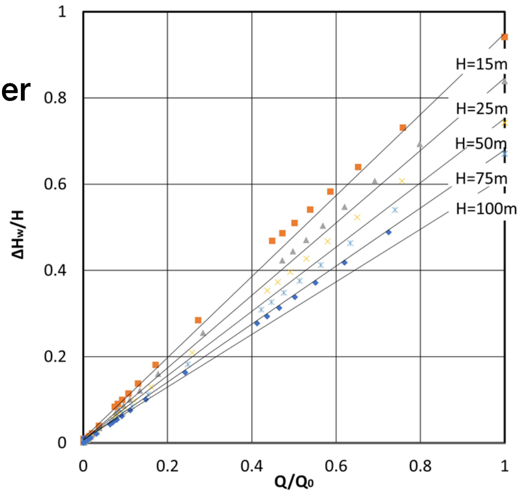
- paths of water and dampness
  :current leakage, electrochemical attacks
- unsafe condition for tunnel users
  :icing conditions and wet walkways
- hydraulic-mechanical interaction
  in the structures
- **damages to the natural environment by lowering the groundwater table**

Hydraulic Environmental Effects due to Leakage

- **Leakage Causes Lowering of Groundwater Table**



Lowering of groundwater table



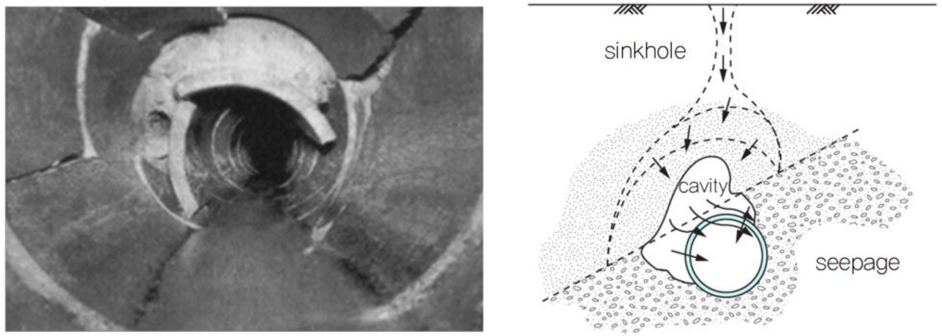
Inflow rate

Relationship between inflow rate and lowering of groundwater table

- **Examples of Leakage-induced Problems**
  - Impact on surface ecosystem: Forest Damage in China
  - The Frogner station in Oslo - 150-200mm of consolidation Settlement
  - Gommarbacken in Stockholm - local brewery supply problem
  - Long-term leakage in erodible soil - depriving lateral support
  - Groundwater level rising in New York City
    → increase leakage of subway tunnel

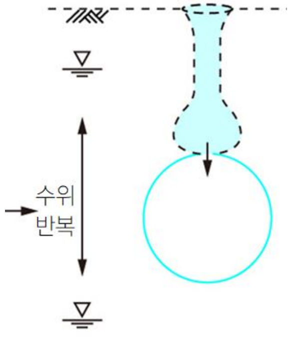
Other Hydraulic Stability Problems

- Hydraulic problems
  - during Excavation
    - hydraulic control
      - drain
        - GW lowering : deep well, well point
        - driven drain : drainage pipe
      - cut–off : 그라우팅
    - hydraulic instability
      - Heaving
      - erosion: piping, sinkhole
      - seepage
  - during Operation
    - soil erosion/cavity, unbalanced e.p.
    - buoyant force
    - pressurized tunnel : clay: hydraulic–fracturing
      rock: hydro–jacking)

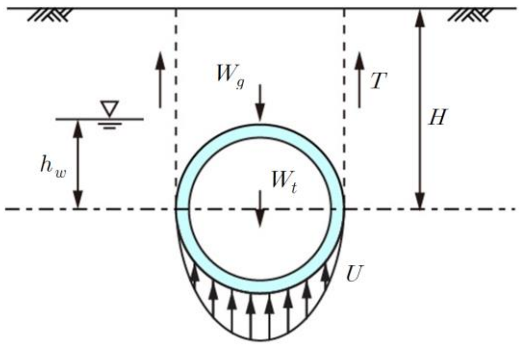


Inflow of Groundwater and Soil Erosion Causing Cavity around a Tunnel

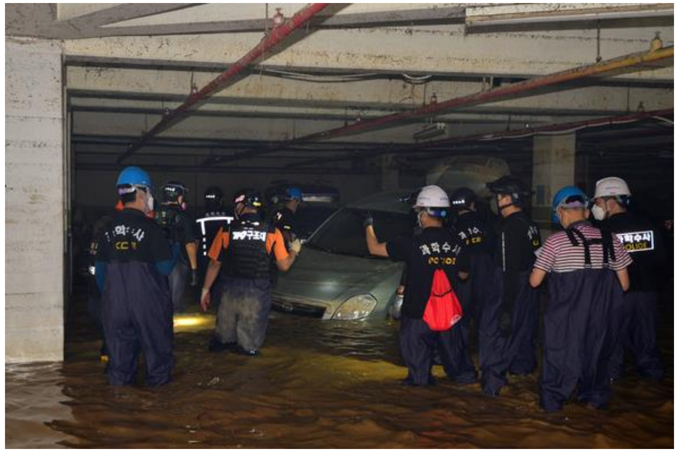
Internal erosion and cavity generation



ground
collapse



Buoyance



Flooded Underground Parking Lot

Hydrological Aspects

Effect of Surface Water on the Underground Structures

$$P = \boxed{Q} + E + \Delta R$$

Q : runoff of surface water

Flooding of Surface Water

$$Q = Qs + \boxed{Qu}$$

Qs : surface runoff

Qu : runoff or storage via underground structures**(floodings)**

Surface Water ➡ Hydrological Aspects
Regional / Land / Urban Problems

Damages of Underground Structures Caused by Surface Water

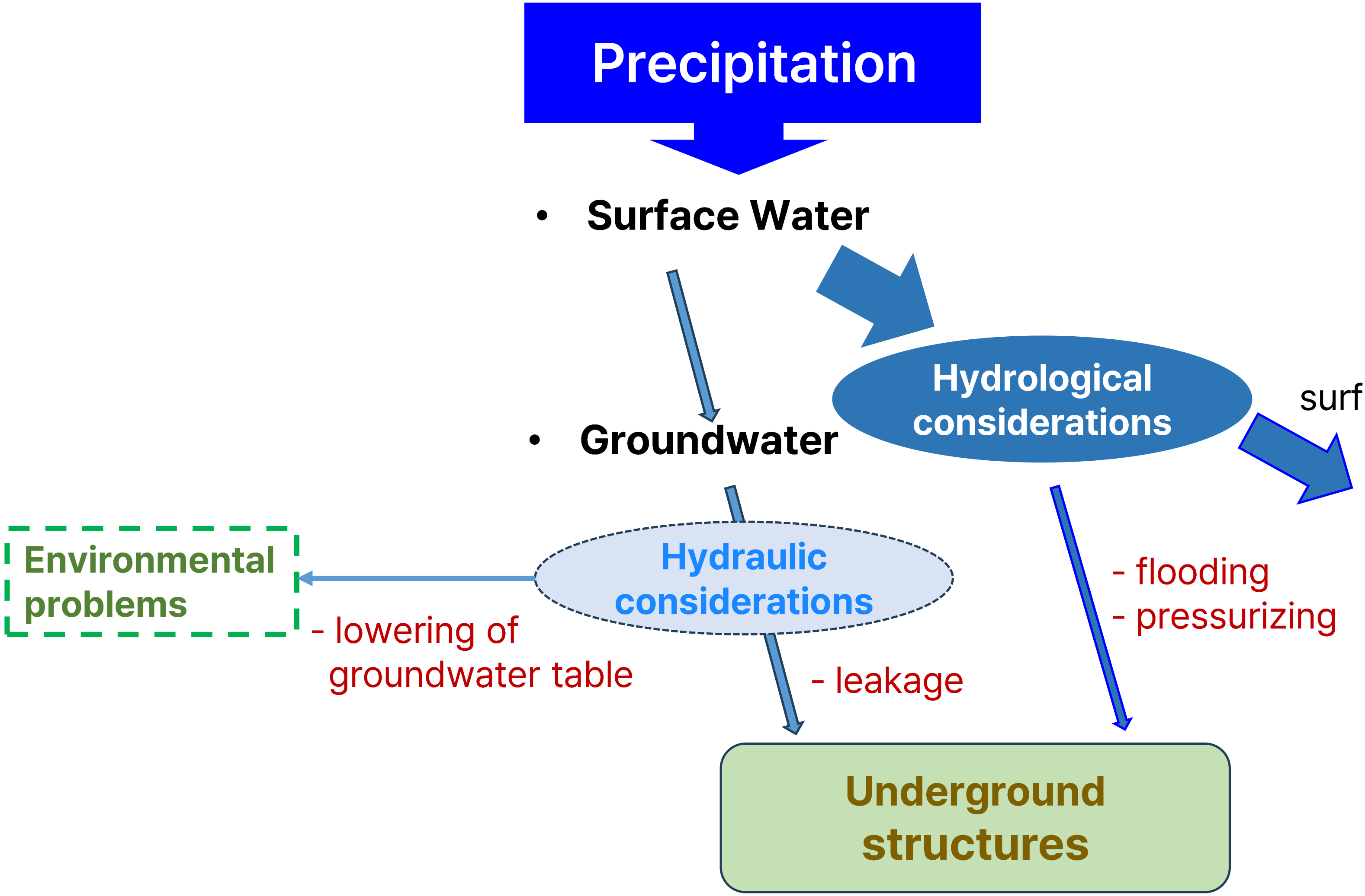
- **Flooding**

8일 밤 서울 동작구 이수역에 빗물이 유입되고 있다. 연합뉴스

- **Pressurizing**

Hydraulic and Hydrological Significance

in the Design of Underground Structures



Precipitation

- **Surface Water**
- **Groundwater**

Hydrological considerations

surface runoff

- flooding
- pressurizing

Hydraulic considerations

Environmental problems

- lowering of groundwater table

- leakage

Underground structures

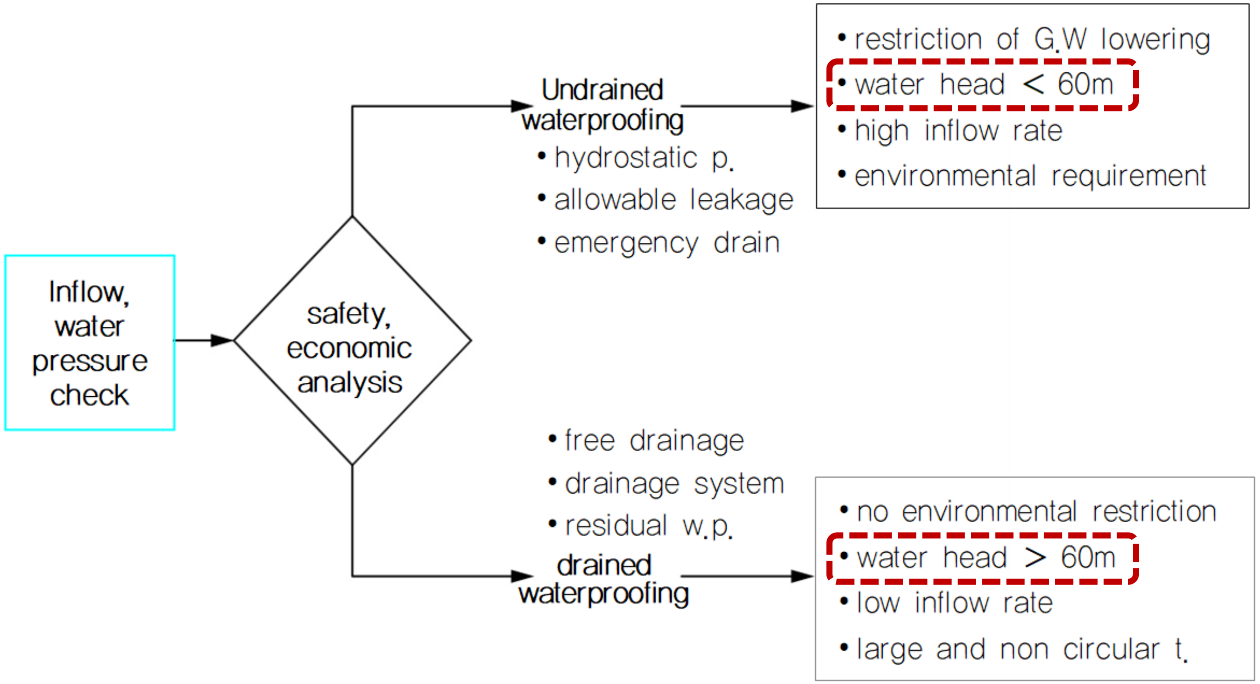
3. Hydraulic Considerations

in the Design of Underground Structures

지하구조물 설계의 수리학적 고찰

3.1
Hydraulic Issues on the Design of Underground Structures

Drained or Undrained Waterproofing ?



Inflow, water pressure check

safety, economic analysis

Undrained waterproofing

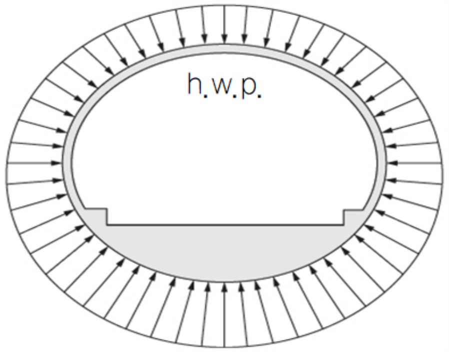
- hydrostatic p.
- allowable leakage
- emergency drain

- restriction of G.W lowering
- water head < 60m
- high inflow rate
- environmental requirement

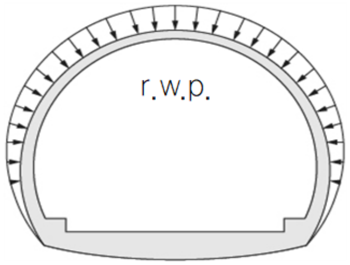
drained waterproofing

- free drainage
- drainage system
- residual w.p.

- no environmental restriction
- water head > 60m
- low inflow rate
- large and non circular t.

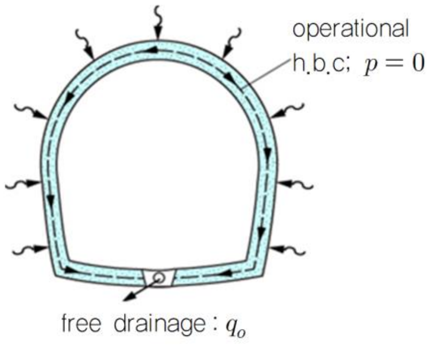


Undrained Tunnel : Circular

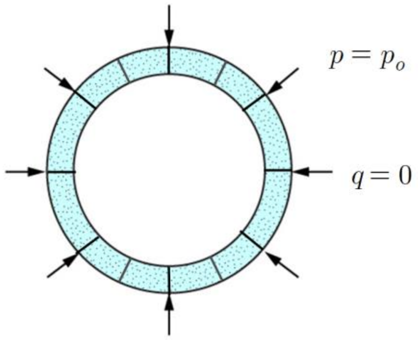


Drained Tunnel : Horse–shoe Shaped

H.B.Cs for Drained or Undrained Waterproofing

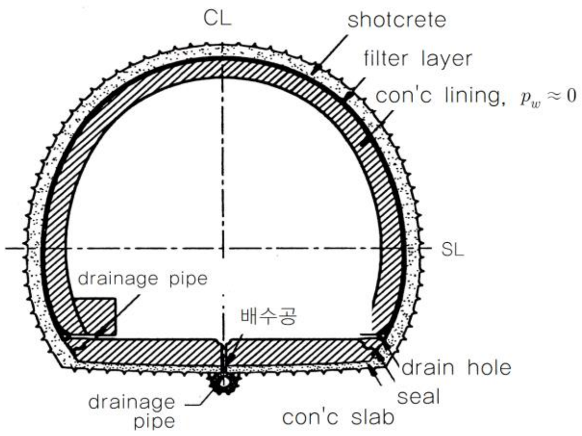


Drained Waterproofing

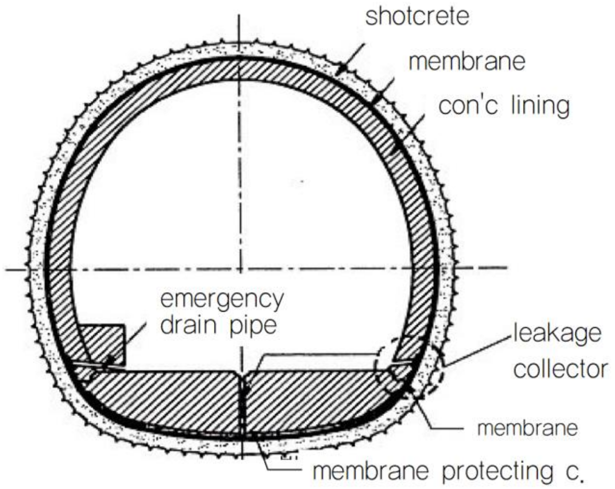


Undrained Waterproofing

Typical Cross Sections



Drained Waterproofing

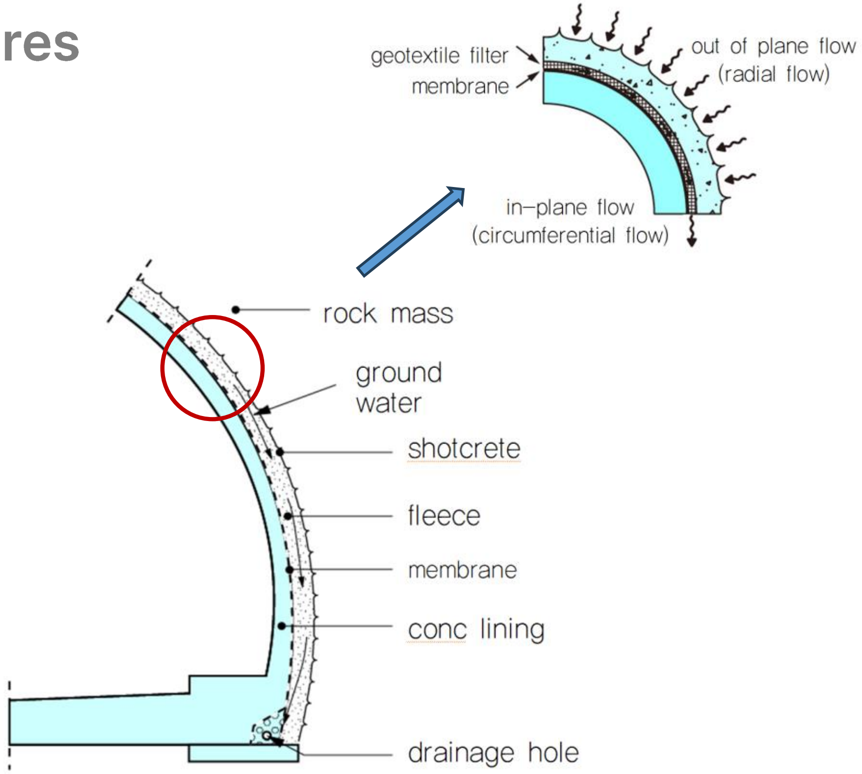


Undrained Waterproofing

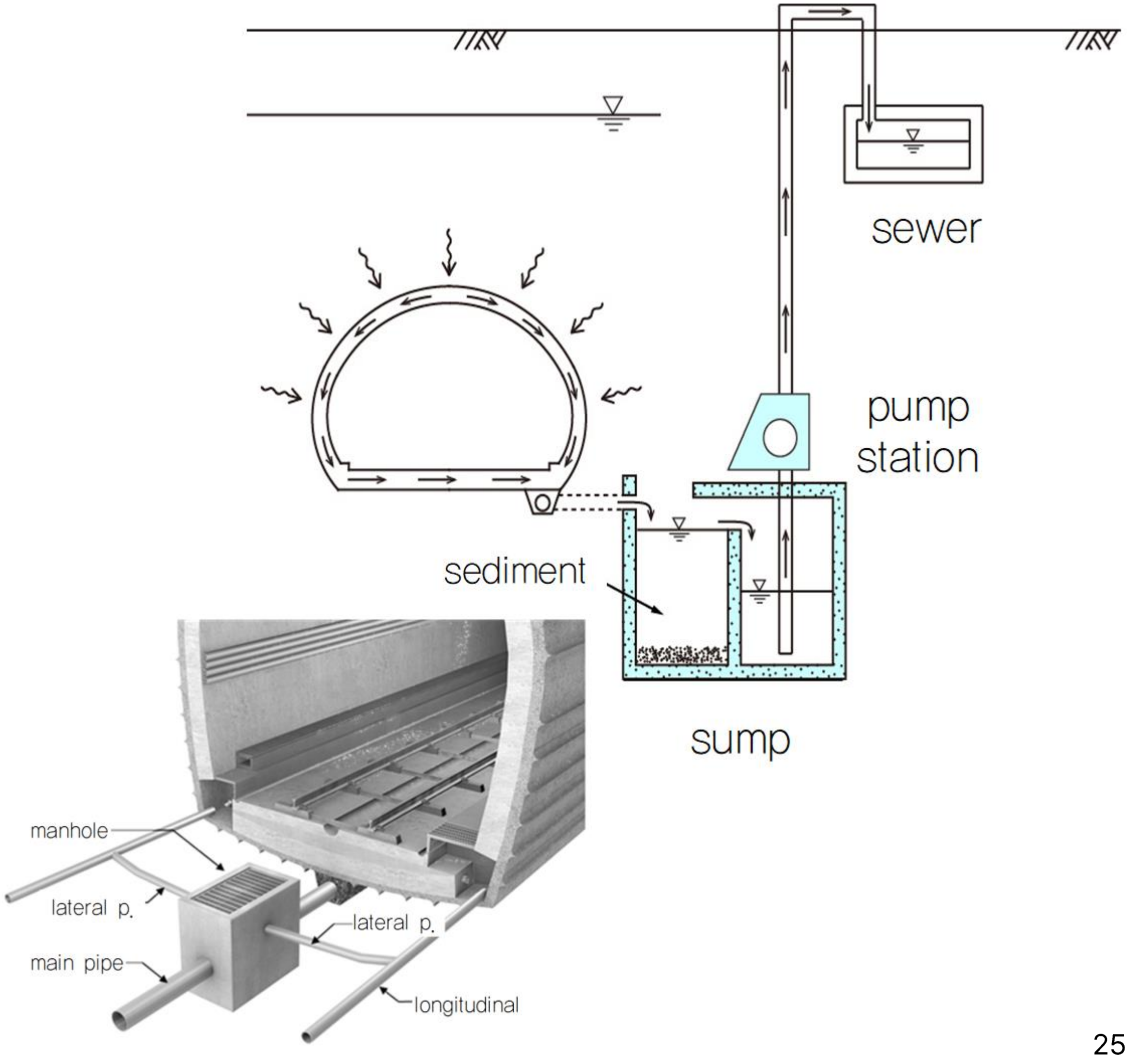
3.1
Hydraulic Issues
on the Design of Underground Structures

Hydraulic Consideration of Drained Tunnel

Drainage System



Drainage System : Lateral Section

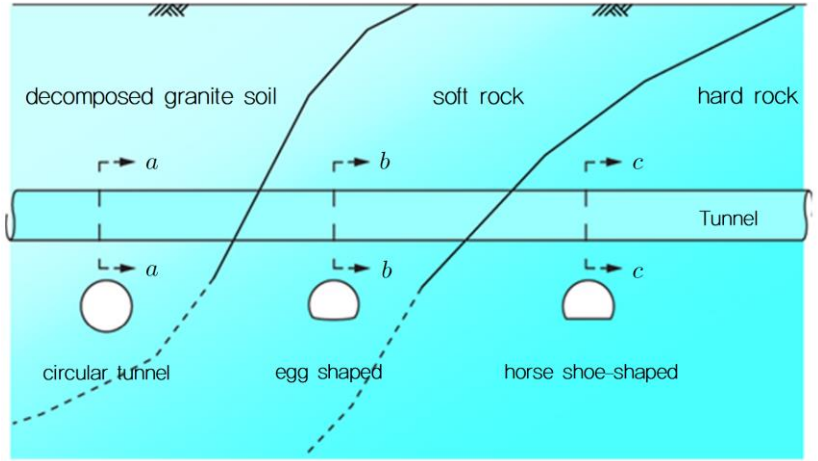


Drainage System : Longitudinal Section

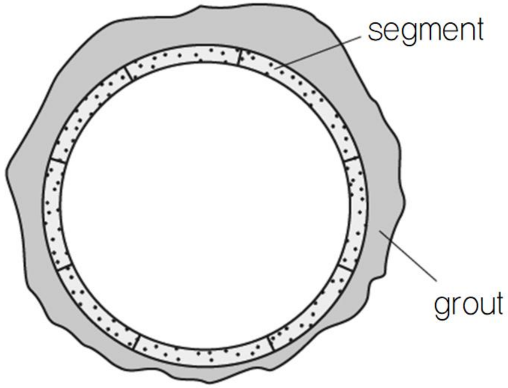
3.1
Hydraulic Issues on the Design of Underground Structures

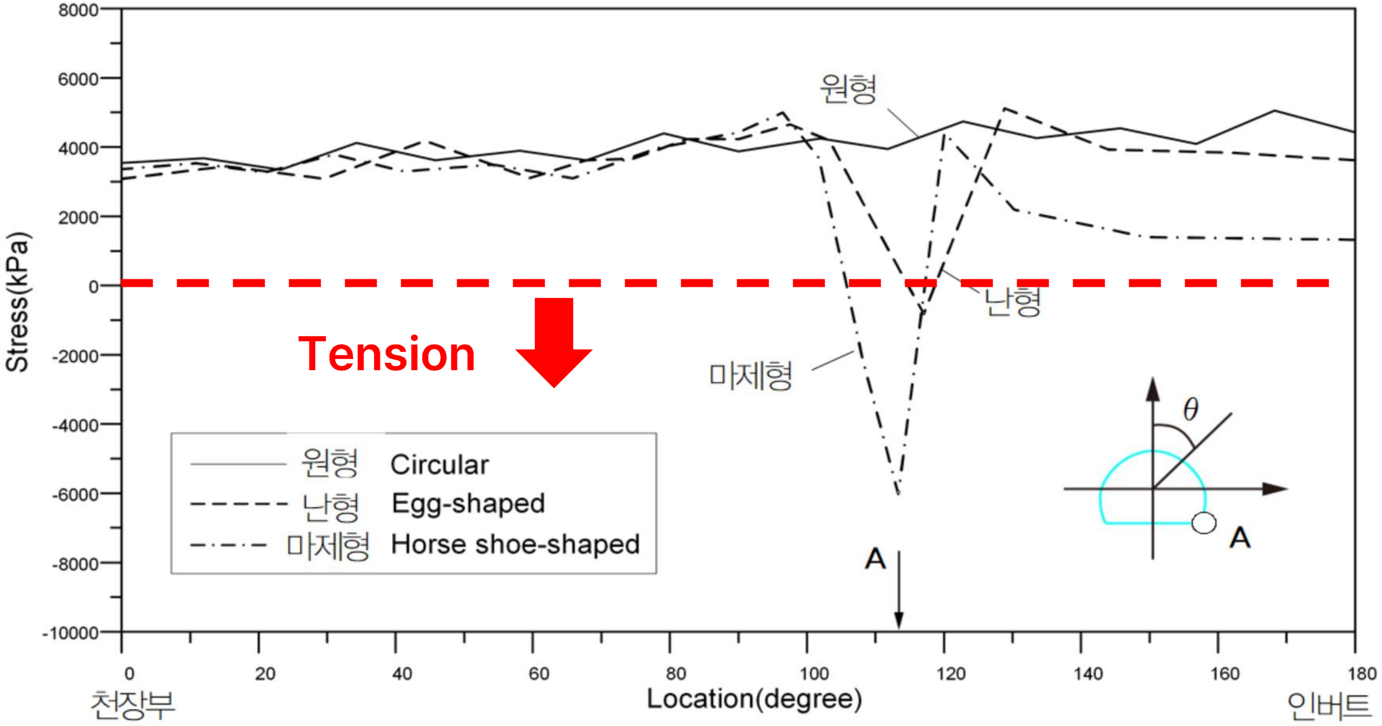
Hydraulic Consideration of Undrained Tunnel

In lining design
just consider hydrostatic pressure
and structural shape,
then, no significant
hydraulic interaction during lifetime.



Effect of tunnel Shape





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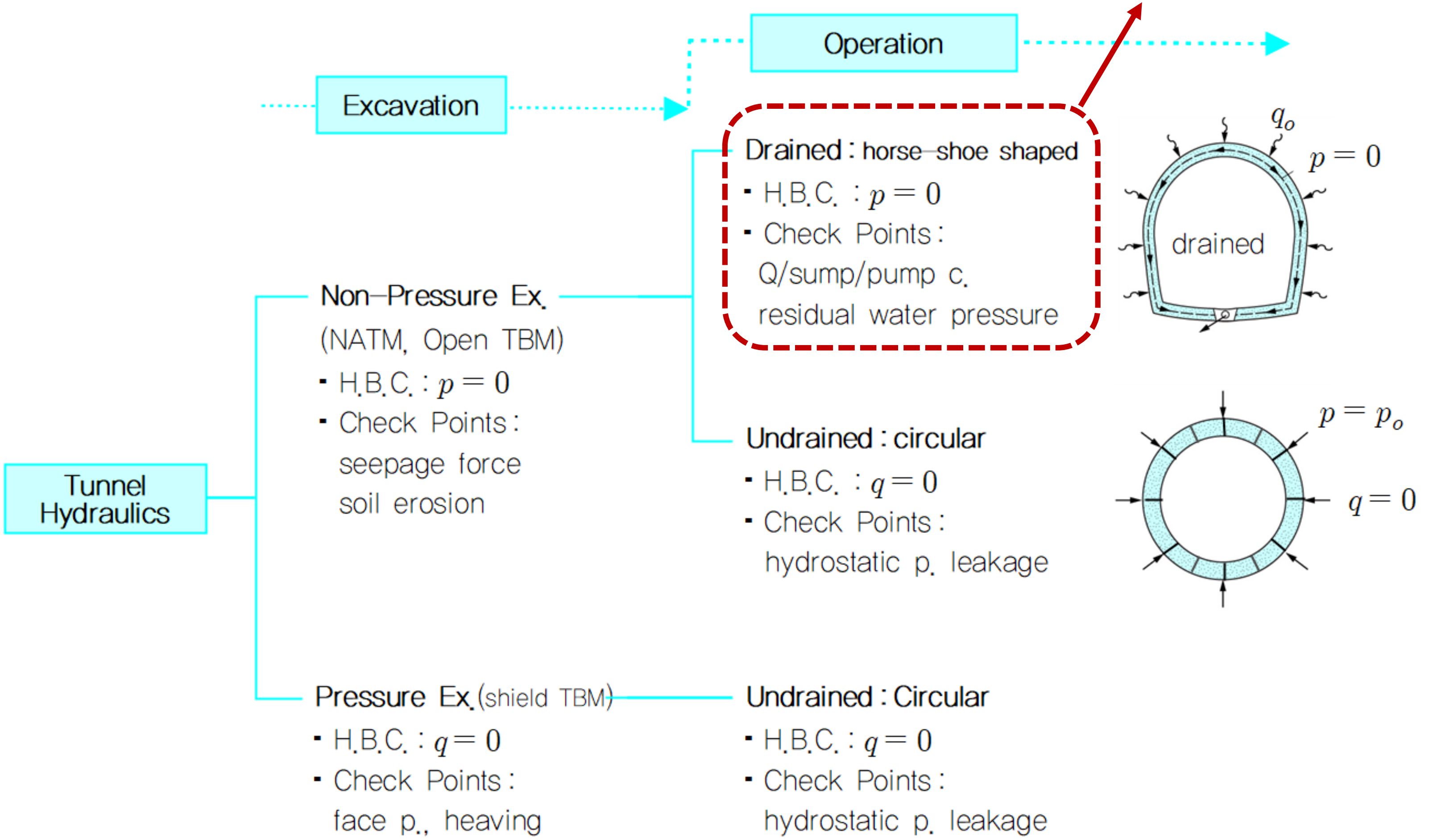
Summary of Hydraulic Issues
on the Design of Underground Structures

Require hydraulic considerations



Tunnel Hydraulics

Excavation

Operation

Non–Pressure Ex.
(NATM, Open TBM)
- H.B.C. : $p = 0$
- Check Points :
  seepage force
  soil erosion

Drained : horse–shoe shaped
- H.B.C. : $p = 0$
- Check Points :
  Q/sump/pump c.
  residual water pressure

Undrained : circular
- H.B.C. : $q = 0$
- Check Points :
  hydrostatic p. leakage

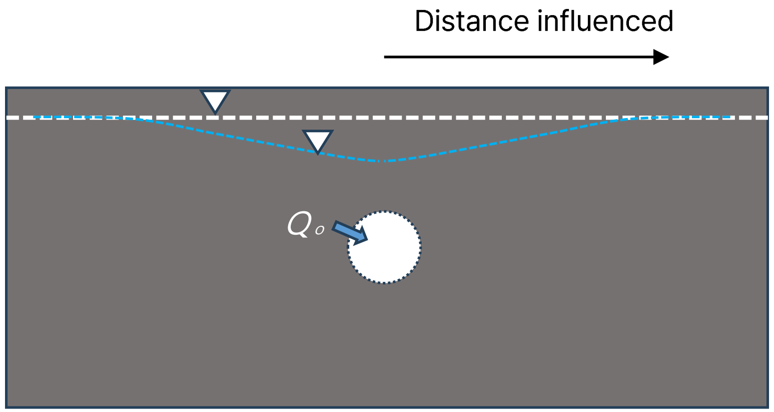
Pressure Ex.(shield TBM)
- H.B.C. : $q = 0$
- Check Points :
  face p., heaving

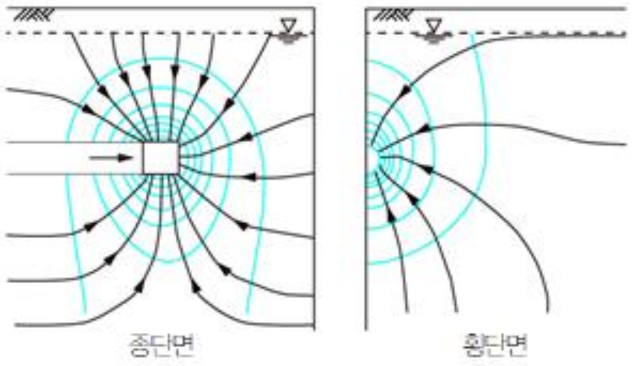
Undrained : Circular
- H.B.C. : $q = 0$
- Check Points :
  hydrostatic p. leakage

Hydraulic Issues and Check Points (p : water pressure, q : inflow rate)

3.2
Hydraulics of Underground Structures:
P-Q Relationship

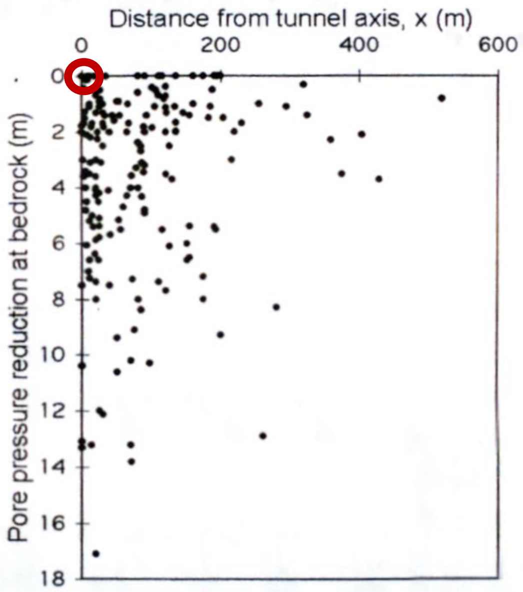
Changes in Groundwater Regime due to Underground Excavation

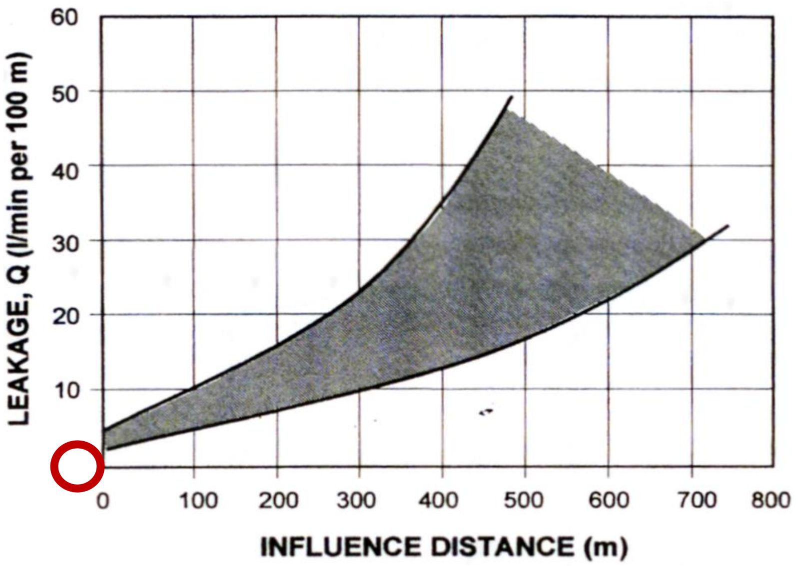




Impacts of Leakage

Observed Pore water pressure reduction
In relation to horizontal distance from tunnel





Typical relationship between influence distance and leakage level

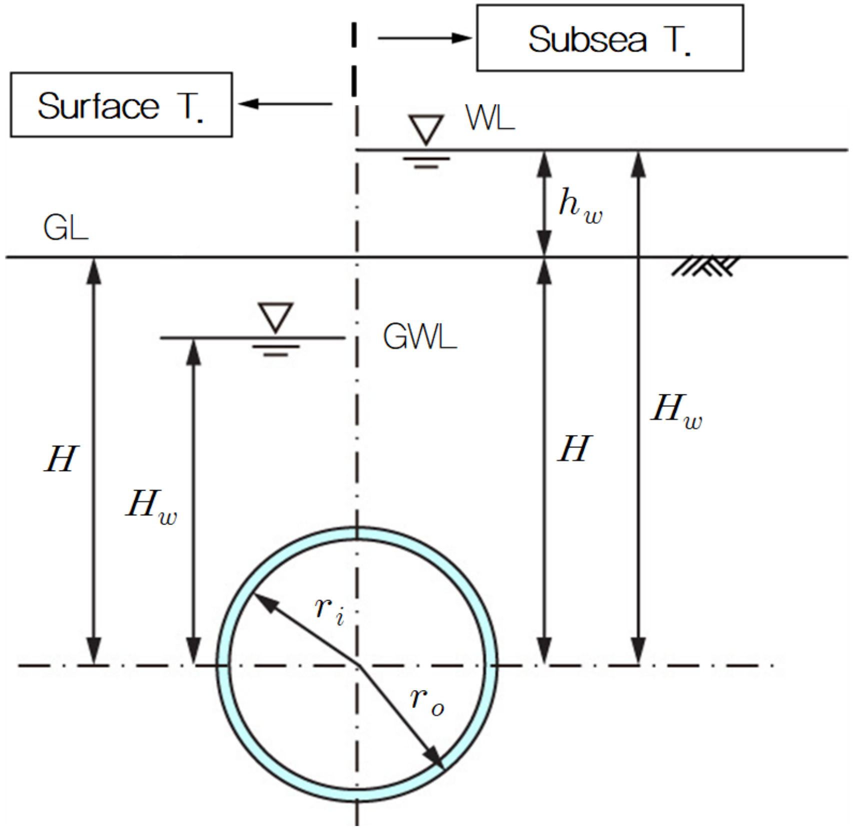
3.2

Hydraulics of Underground Structures:

P-Q Relationship

Tunnel Hydraulics Parameter Definition

(for drained Underground Structures)



H : tunnel depth

H_w : water table

$$H_w = H + h_w$$

h_w : water depth

r_i : inner radius

r_o : outer radius

Controlling Parameters

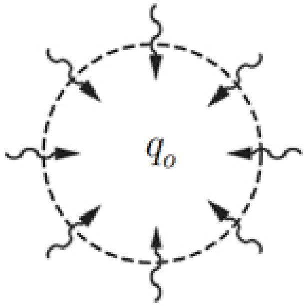
q_0 : inflow from free drainage

p_0 : hydrostatic pressure

3.2
Hydraulics of Underground Structures:
P-Q Relationship

Hydraulics of the Fully Drained Tunnel

Free Drainage



Goodman et al. (1965)

$$q_o = 2\pi \boxed{k_s} \frac{H_w}{\ln\left(\dfrac{2H_w}{r_o}\right)}$$

Inflow rate is linearly proportional to ground permeability

High Inflow Rate →

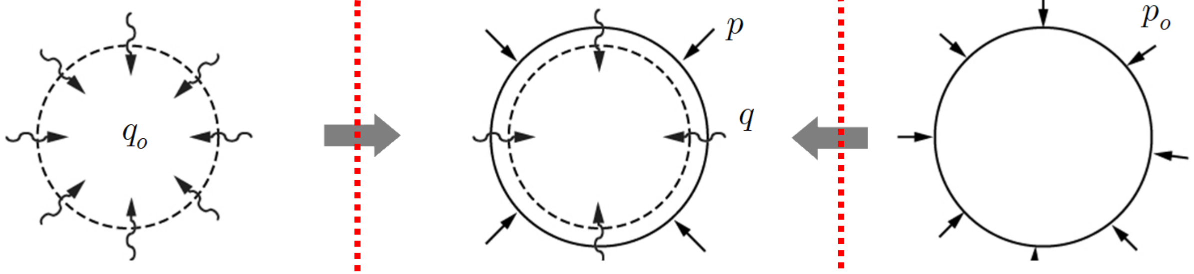
High Maintenance Cost

Control of Leakage

- to reduce inflow and operational cost
- to improve service conditions
- to measure hydraulic deterioration

3.2
Hydraulics of Underground Structures:
P-Q Relationship

Free Drain (q_o) | **Limited Drainage** (q_l , p_l) | **Non-drainage** (p_o)



Fully Permeable ($p = 0,\ q = q_o$)

Limited Permeable ($p < p_o,\ q < q_o$)

Impermeable ($p = p_o,\ q = 0$)

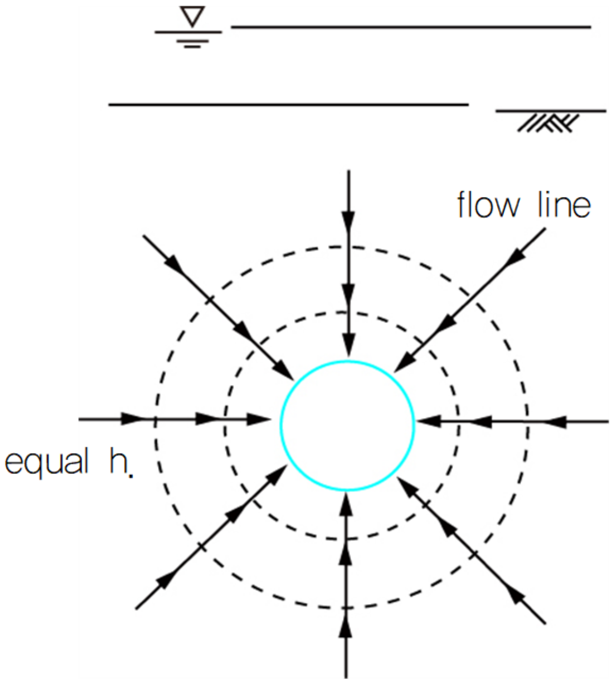
	Free drainage	Limited Drainage	Non Drainage
Water Pressure	0	$p_o < p_l < 0$	p_o
Inflow Rate	q_o	$0 < q_l < q_o$	0

Principle of Leakage Control

Purpose of Leakage Control

- to reduce inflow
- to reduce water pressure on the lining

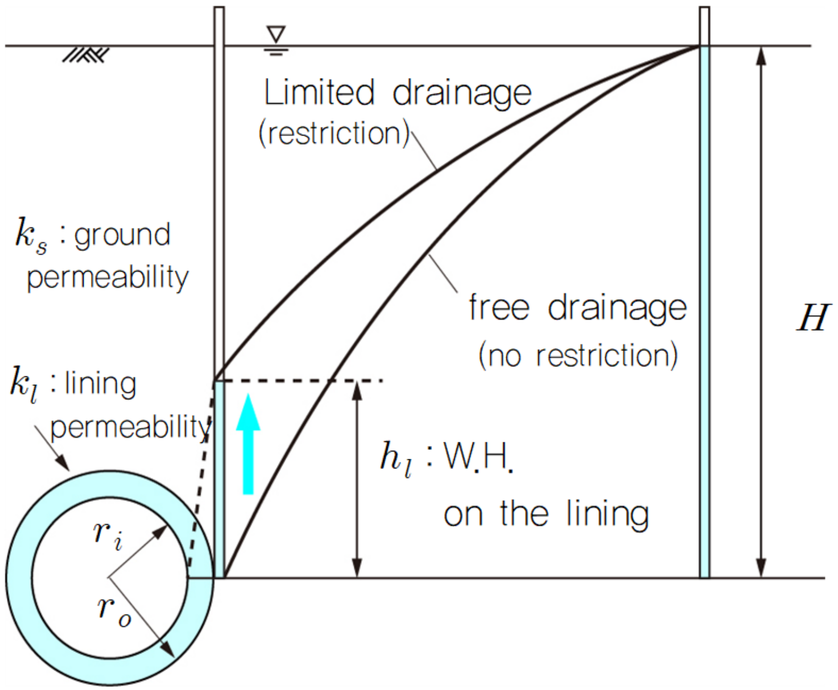
Free Drainage



Radial Free Drainage

Free Drainage
q_o , p_o=0

Limited Drainage



Flow Restriction and Water Head Development

Limited Drainage
q_l, p_l

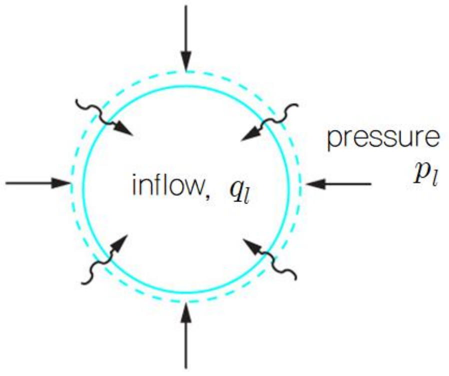
Relationship between Inflow Rate(Q) and Water Pressure(P)

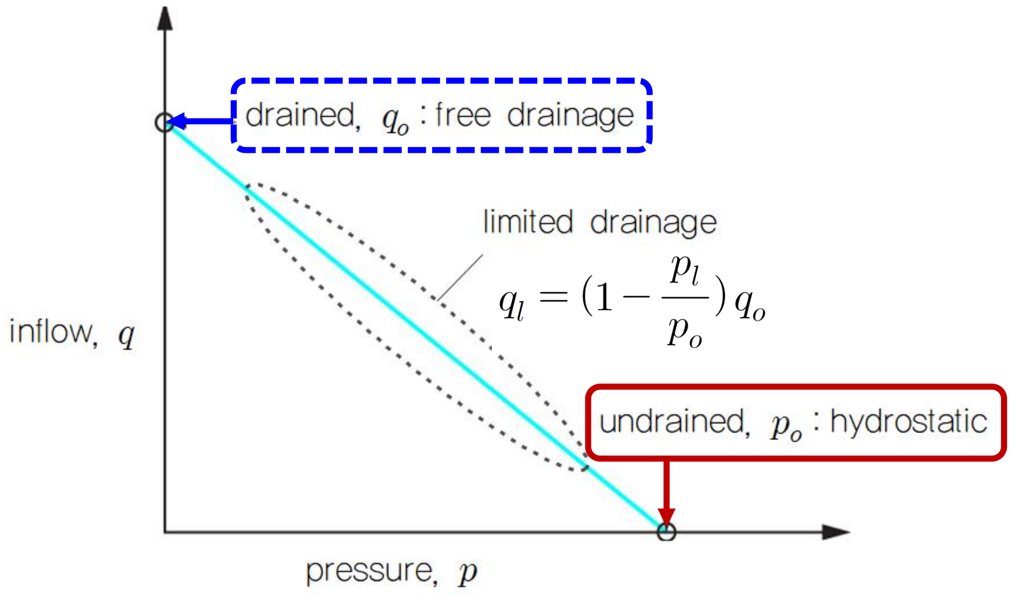
Joo and Shin(2014)

$$\boxed{q_l = \left(1 - \frac{p_l}{p_o}\right) q_o}$$

p_o : hydrostatic pressure
p_l : water pressure on the lining
q_o : free drainage(theoretical evaluation)
q_l : measured inflow rate

Limited Drainage





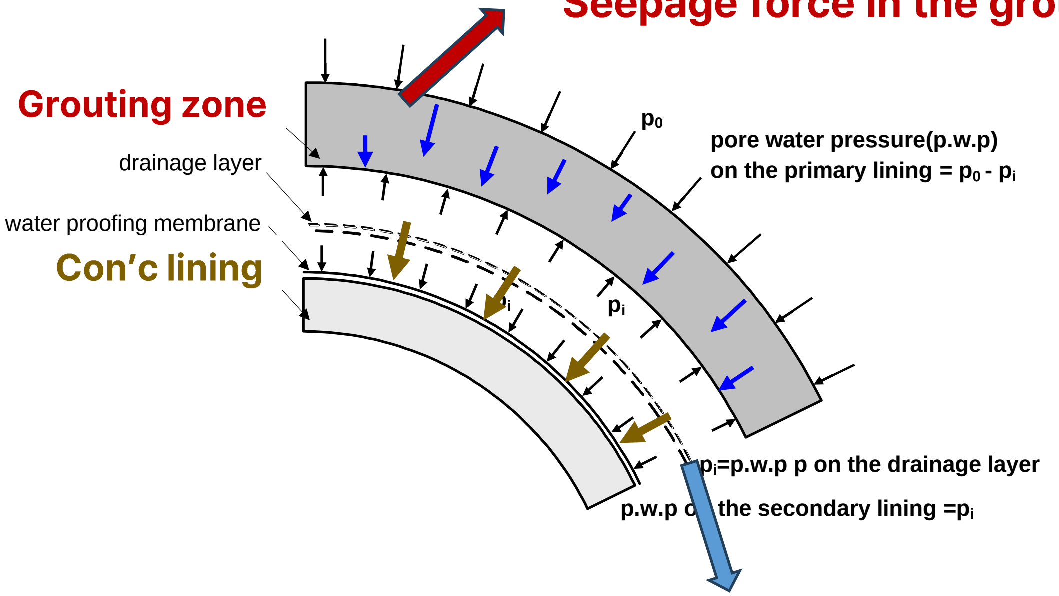
$p_l - q_l$ Relationship

Reduction of Inflow creates water pressure

3.2
Hydraulics of Underground Structures:
P-Q Relationship

Principle of P-Q Control

1. Grouting
Seepage force in the grouting zone



2. Reduction of permeability of drainage layer
Water Pressure on the Lining

Supporting Method of Water Pressure

Leakage control can create **water pressure, or** **seepage force.**
(on the lining) **(in the ground)**

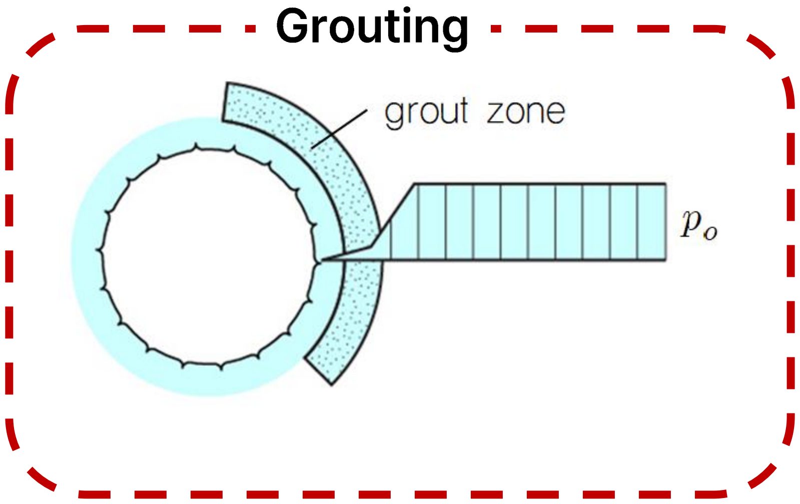
Grouting

3.3
Drainage Control

Strategy of Drainage Control

- Reduce inflow rate
- without increase in lining thickness

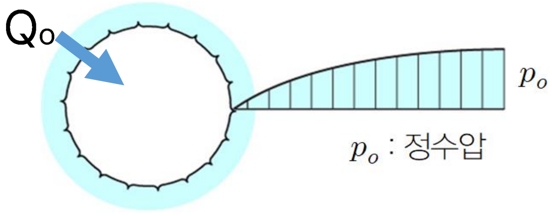
Grouting



Limited Drainage

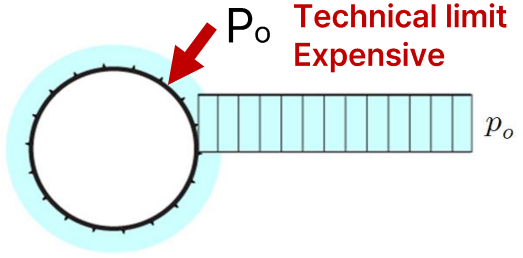
Free Drainage

High maintenance cost



Free Drainage

Non-drainage



Technical limit
Expensive

Watertight(non–drainage)

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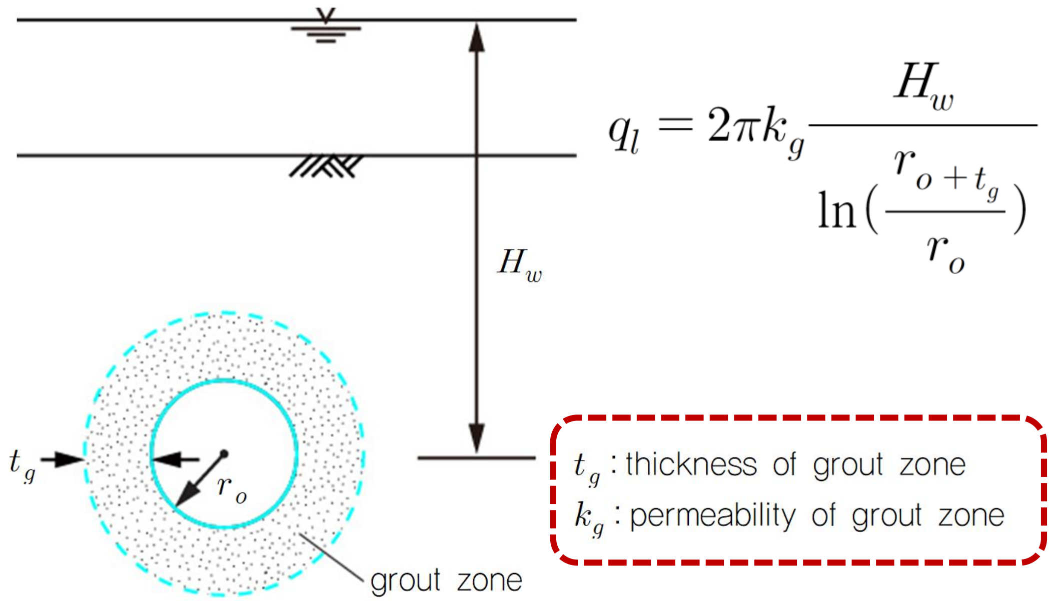
Drainage Control

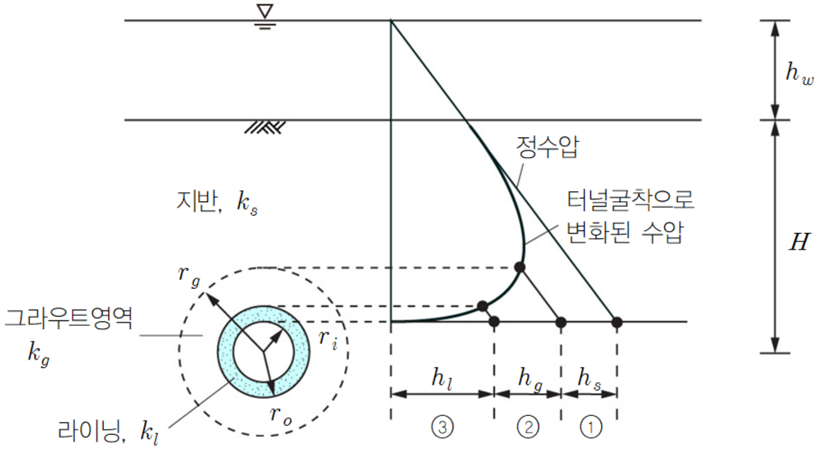
Limited Drainage by Grouting (Karlsrud,2001)



$$q_l = 2\pi k_g \frac{H_w}{\ln\left(\frac{r_o + t_g}{r_o}\right)}$$

t_g : thickness of grout zone
k_g : permeability of grout zone

Mechanism of Water Head Loss by Grouting



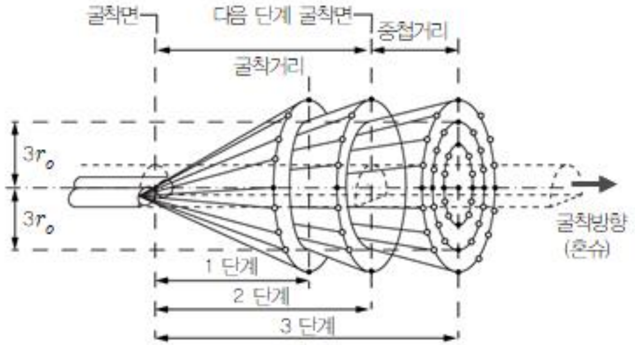
① 원지반의 부담 수두 : $h_s \fallingdotseq H + h_w - h_l - h_g$
② 그라우트 존의 부담 수두 : h_g
③ 라이닝의 부담 수두 : h_l

Benefits from Drainage Control

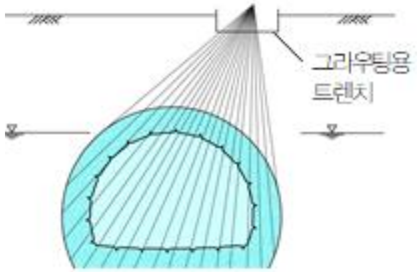
- reduce inflow rate
- prevent lowering of groundwater table
- reduce pumping capacity
- economic design of lining

3.3 Drainage Control

Leakage Control : Pre-grouting (Ref: NGI Pb #12)

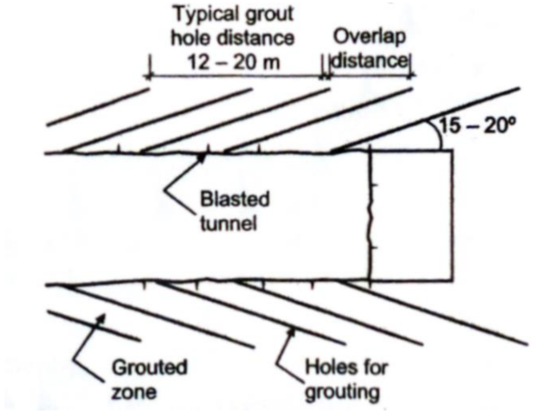


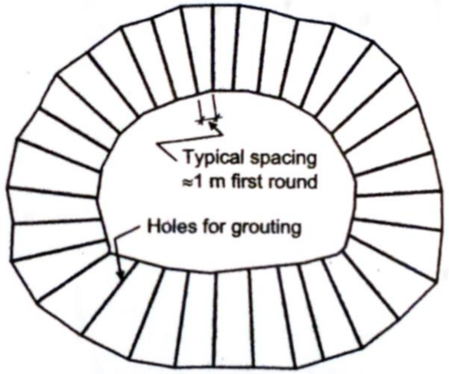
Seikan tunnel



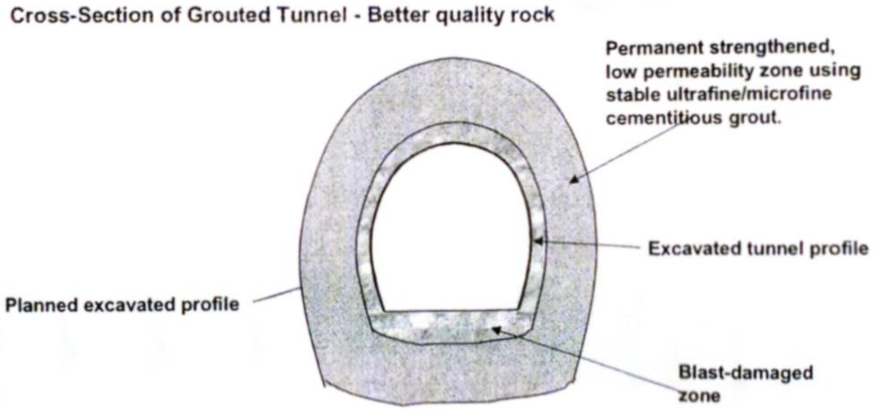
Caracas Metro

- **Principle**

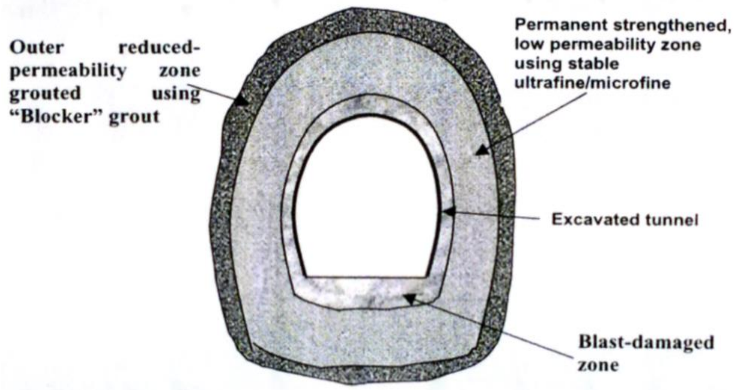




- **Application**



Good rock



Poor rock
(Ref: NGI Pb #12)

Examples of Drainage Control in Subsea Tunnels

Name Of Tunnel	Land length (km)	Sea Length (km)	Water depth (m)	Rock cover (m)	Drainage type	Allowable leakage (m^3/m.d)	Construction method
Seikan, Japan	30.55	23.3	140	100	drained	0.2736	advanced grouting /Mine Tunneling Method
관문공로 터널 Japan	2.681	0.78					advanced grouting /Mine Tunneling Method
새 관문터널 Japan	17.833	0.88	29	24	drained /방수식		advanced grouting /Mine Tunneling Method
Norway 해저터널	4.358	3.30	100	40	drained	0.432	drilling and blasting method
단마르크 특대해협터널	7.900	75.00	20		drained	0.143	tunneling machine (*D* = 7.7 m)
Channel Tunnel	-	49.000	21～70		drained /방수식		tunneling machine (*D* = 7.8 m)
Tokyo Bay Tunnel	동경만 터널		60		undrain-ed		shield machine
Norway Byfjord Subsea Tunnel	5.800(sea+land)		Sea level depth —223 m		drained	0.046	drilling and blasting method
Norway Mastrafjord Subsea Tunnel	4.400(sea+land)		Sea level depth —132 m		drained	0.072	drilling and blasting method

3.3 Drainage Control

Example of Tunnel with Limited Drainage
- Seikan Tunnel, Japan

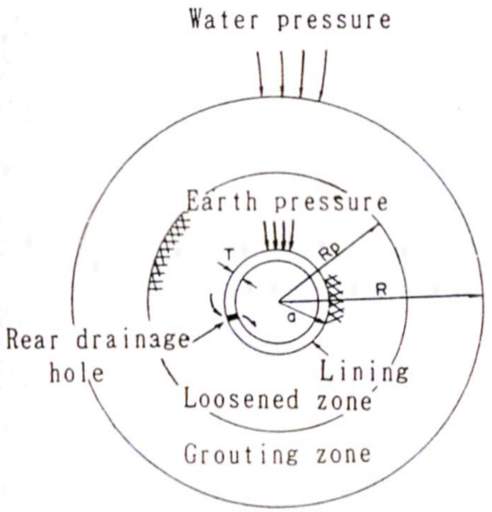
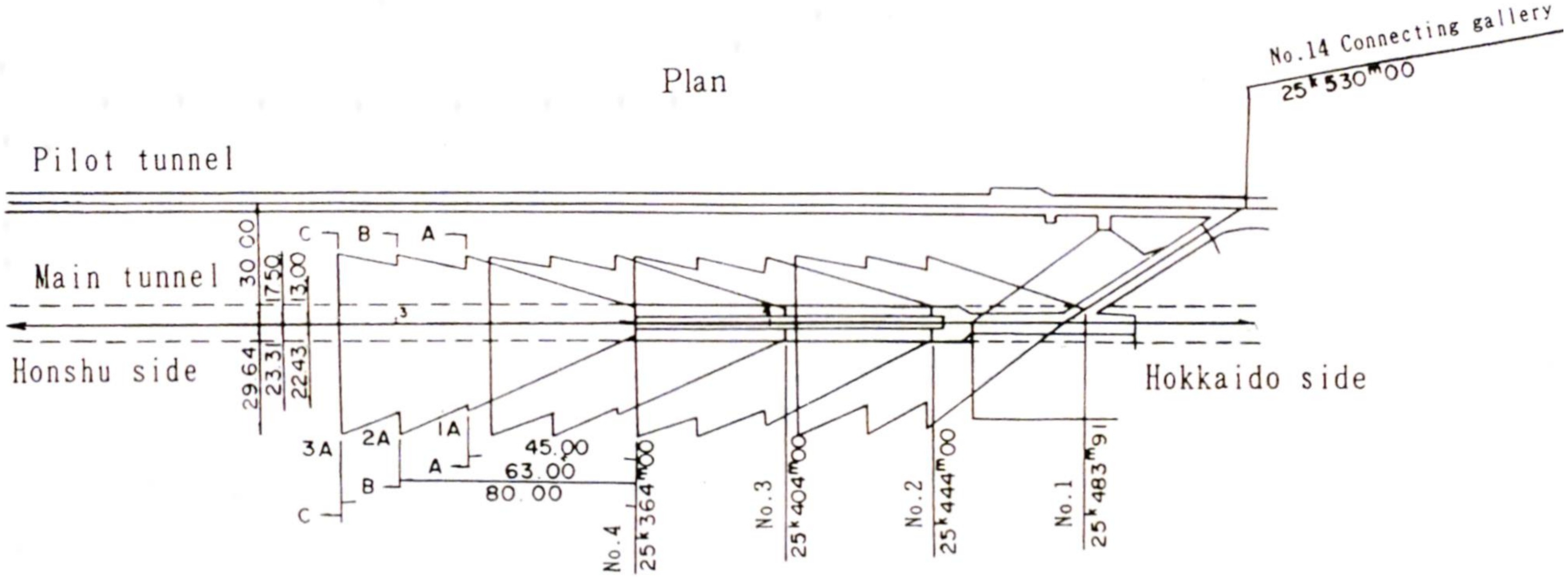


Figure 3. Model diagram of the grouting zone (a=radius of excavation; T=thickness of lining; R=radius of grouting; R_p=radius of the loosened zones).



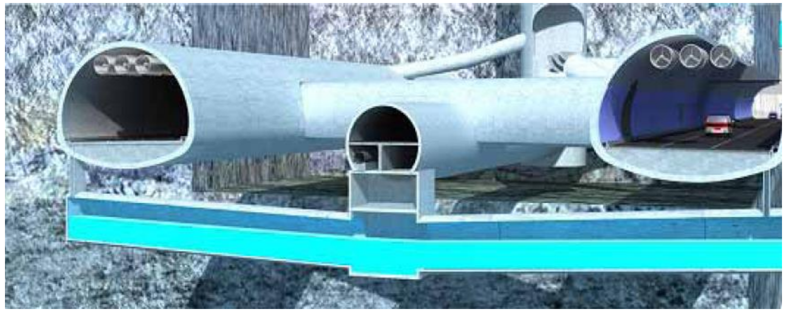
L(sea distance) = 23.3km
D = 11m
Max Water Head = 24bar

Drainpipes

Pumping station

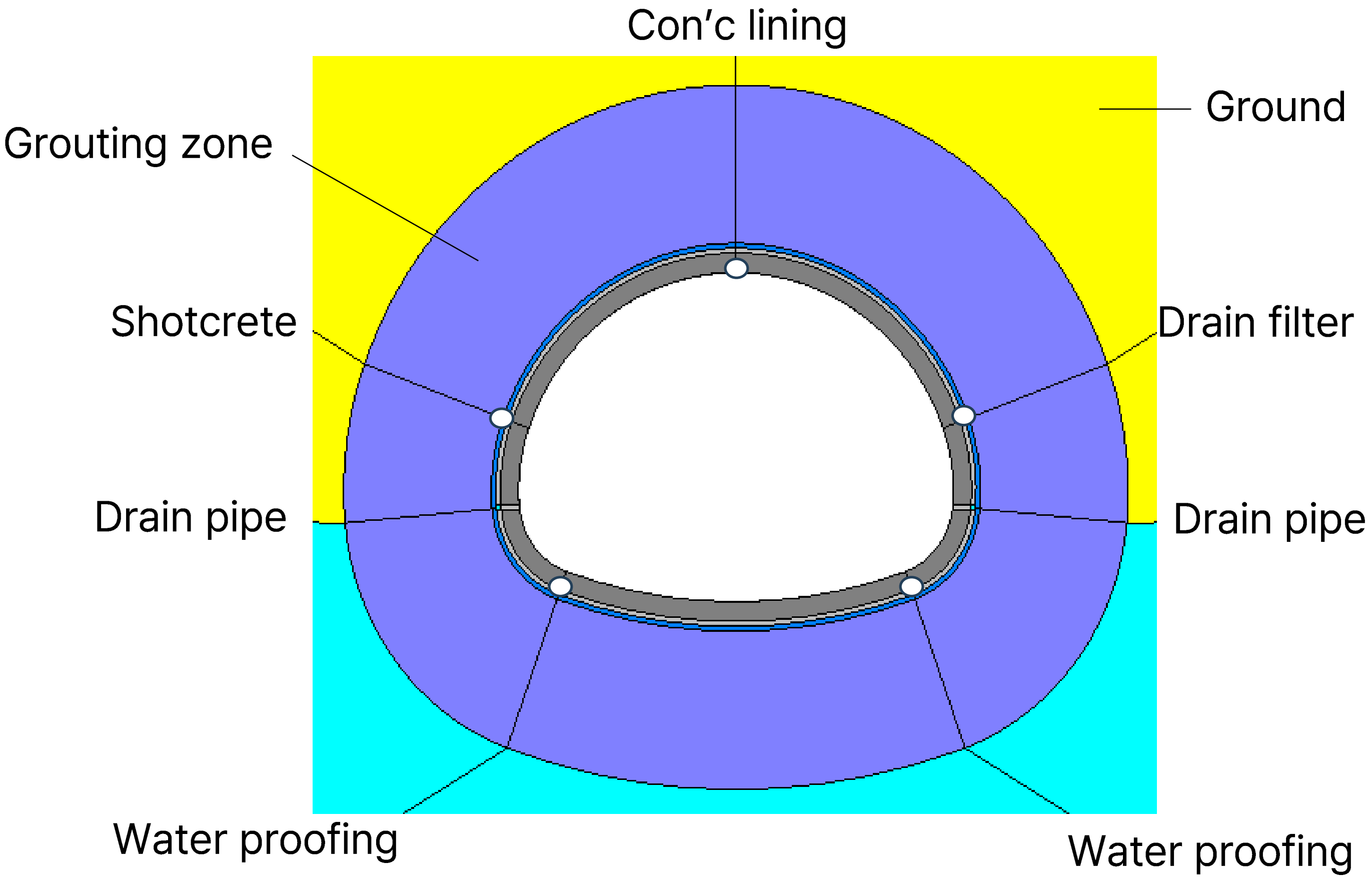
Example of Tunnel with Limited Drainage
- Shamen Subsea Tunnel, China, 2009

Water pressure distributed in the ground in the form of seepage force, therefore, lining water pressure reduces significantly by allowing drain.



Major sump

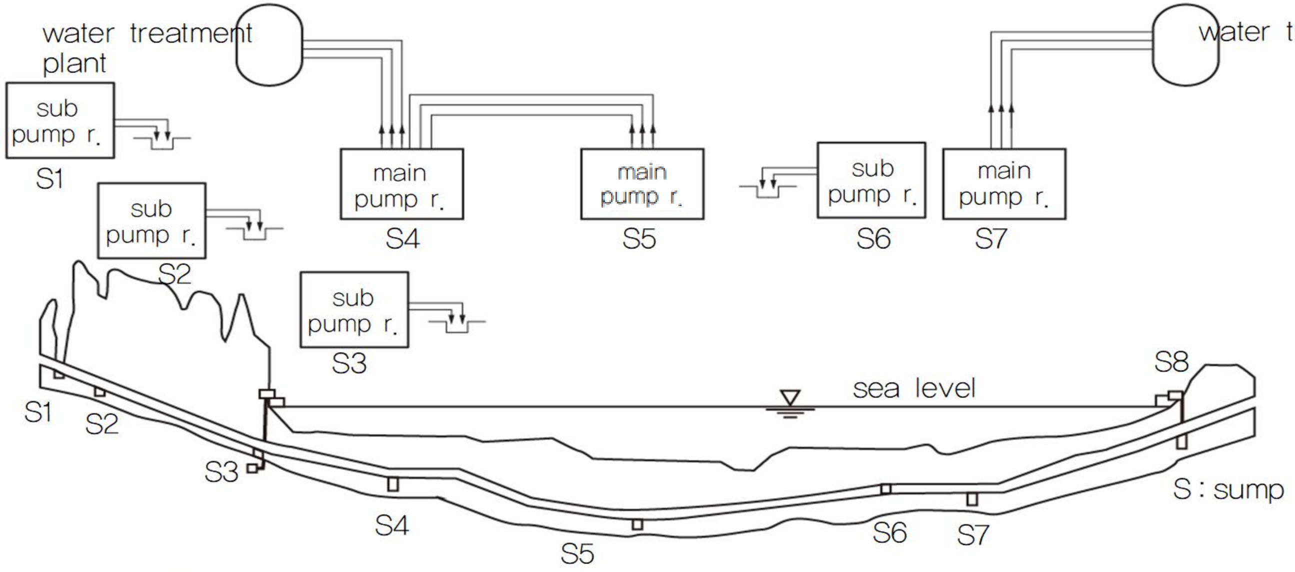
L(sea distance) = 5.95km
D = 13.5m

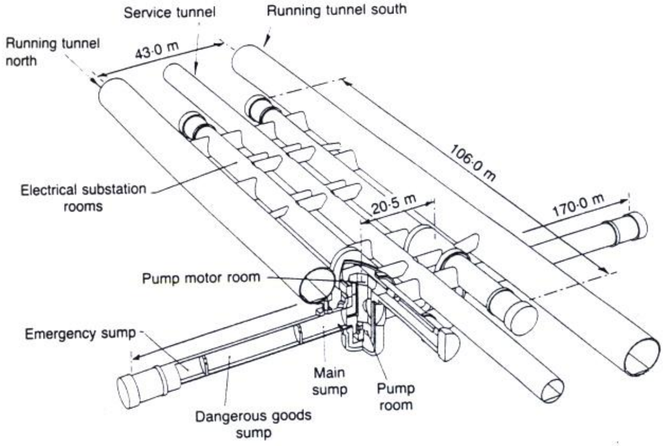


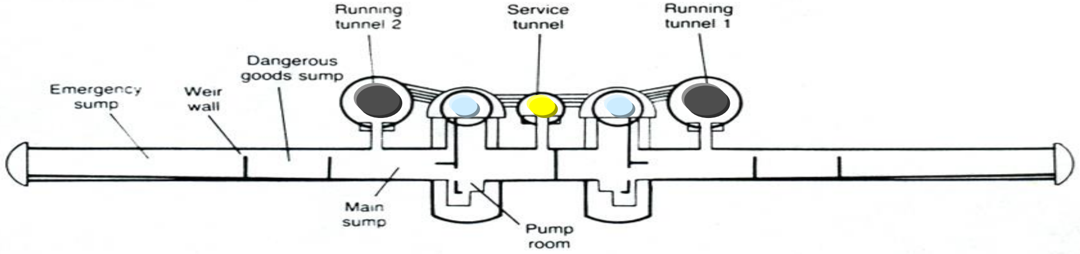
Water Collecting and Pumping System in the Channel Tunnels

Channel Tunnel between UK and France

L(sea distance) = 37.9km
D = 2 x 7.6m
Max Water Head = 10bar



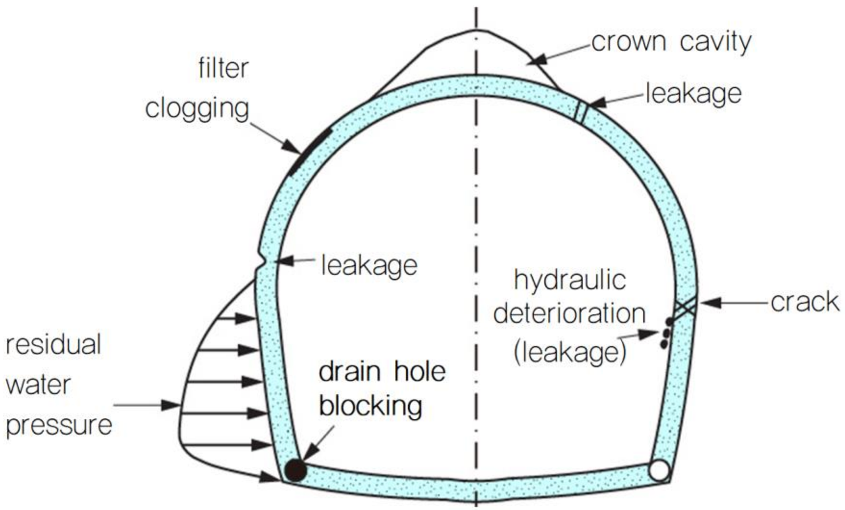




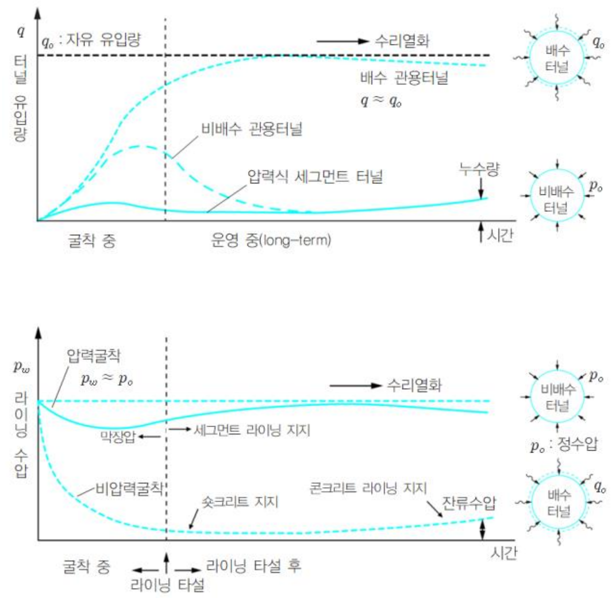
3.4
Long-term Hydraulic Deterioration

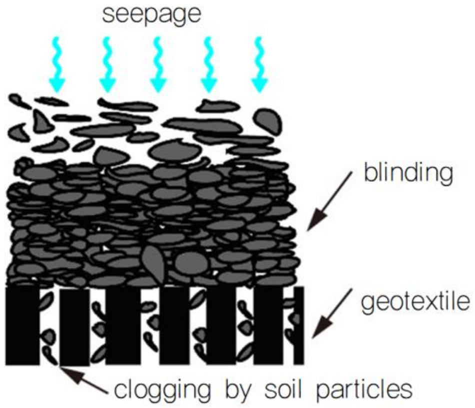
Tunnel Lifetime=120Years

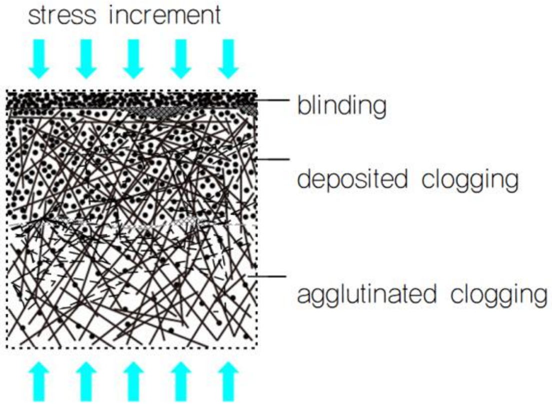
Hydraulic Deterioration



Changes of H.B.Cs in the lifetime of tunnel

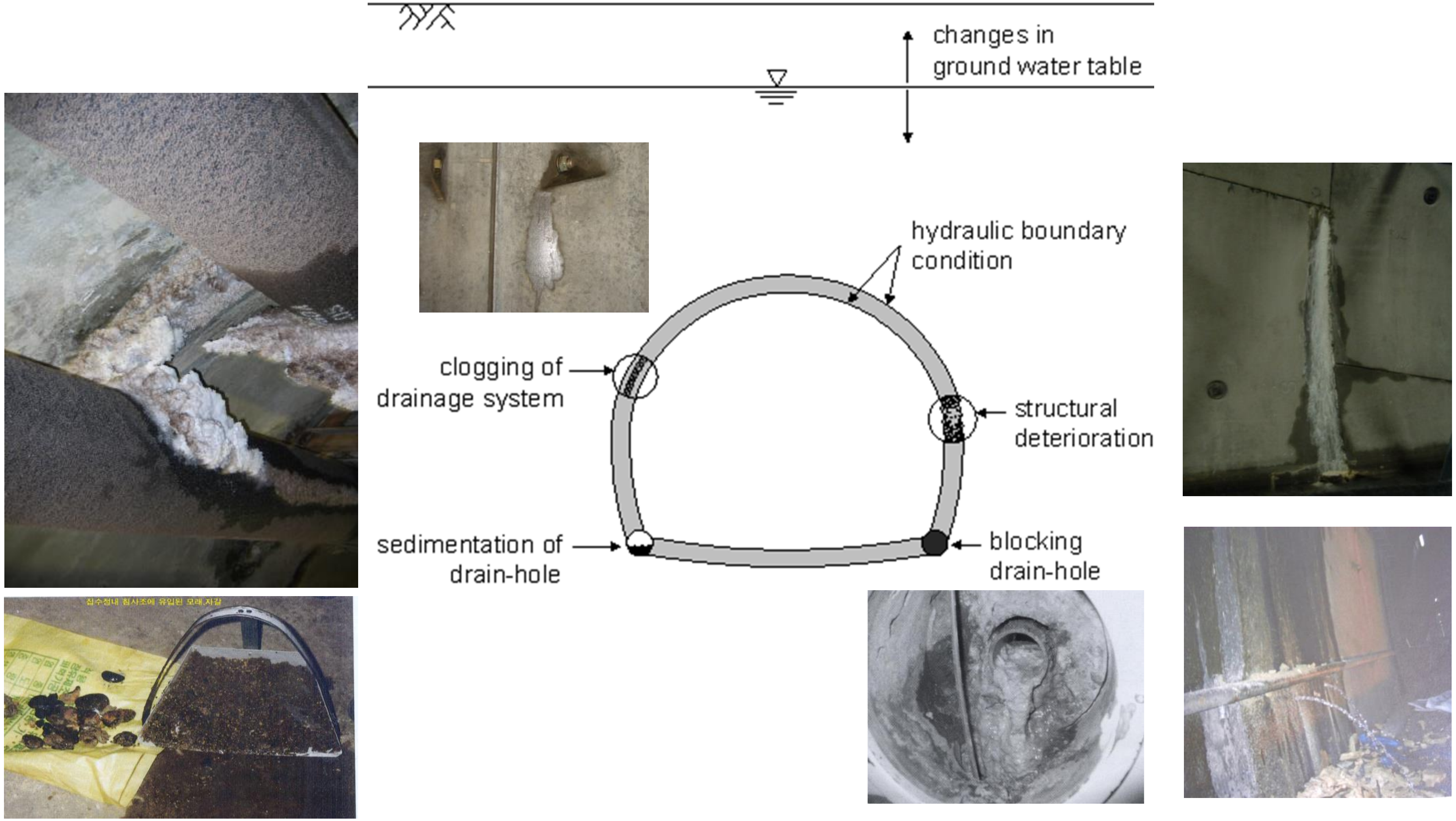






3.4
Long-term Hydraulic Deterioration

Evidences of Hydraulic Deteriorations



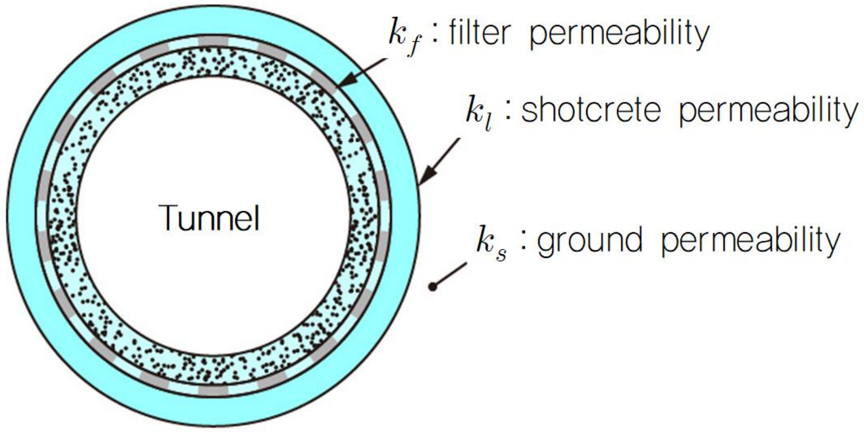
3.4
Long-term
Hydraulic
Deterioration

Understanding of
Hydraulic Deterioration of Drainage System

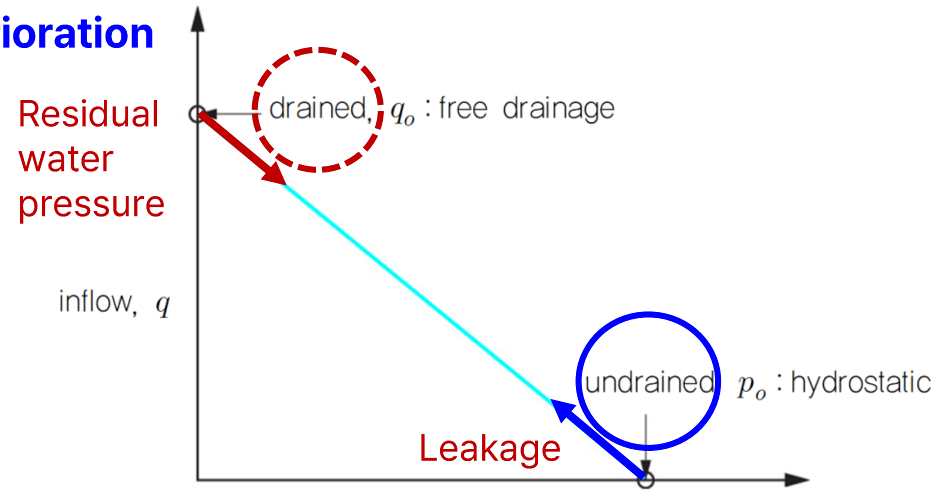
- Groundwater flow path: ground → shotcrete → filter → drainpipe → sump
- Design H.B.Cs change with time

Influencing Factors

- deterioration of drainage system
- rock weathering
- adjacent construction
- chemical attacks



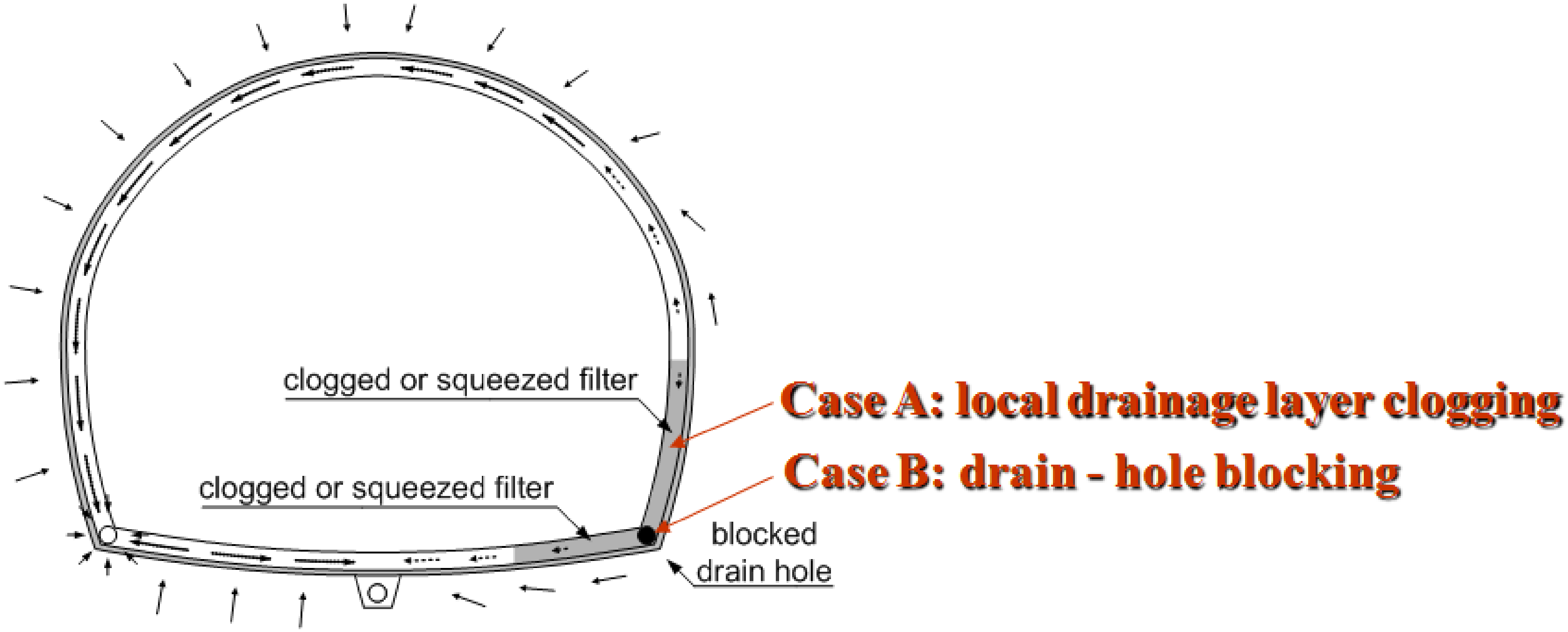
Hydraulic Deterioration



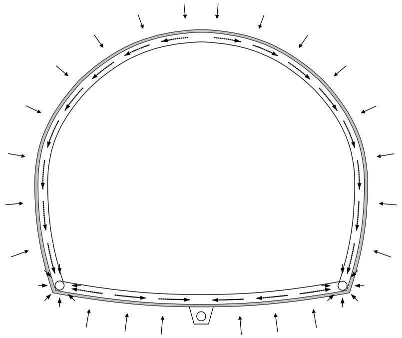
Long-term Hydraulic Deterioration of Drainage System

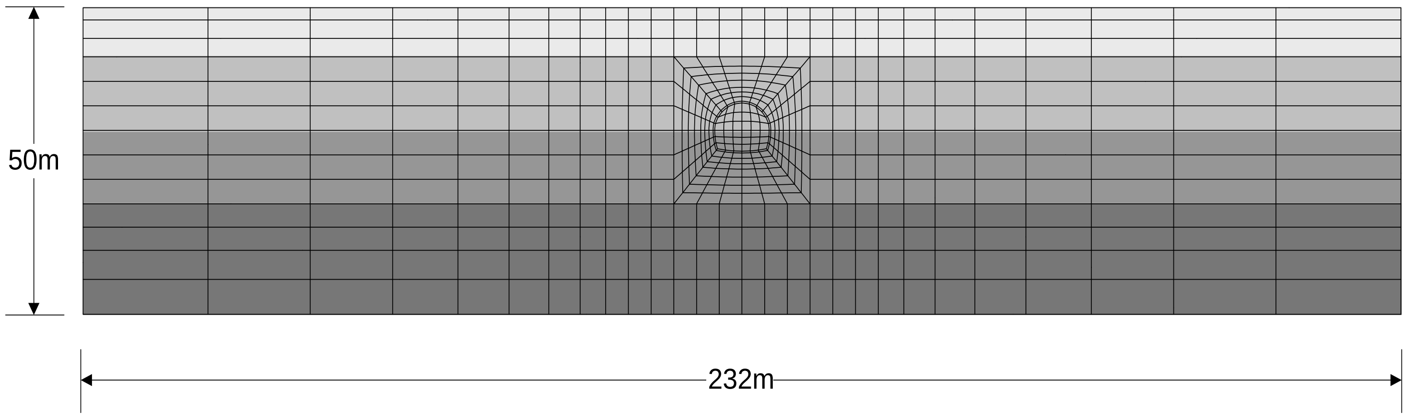
Investigation of the Effects of Hydraulic Deterioration

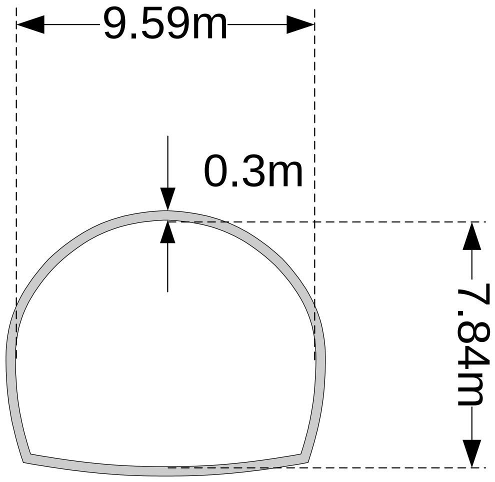
- squeezing and clogging of drain filters (Case A)
- blocking of drainpipe or drain-hole (Case B)

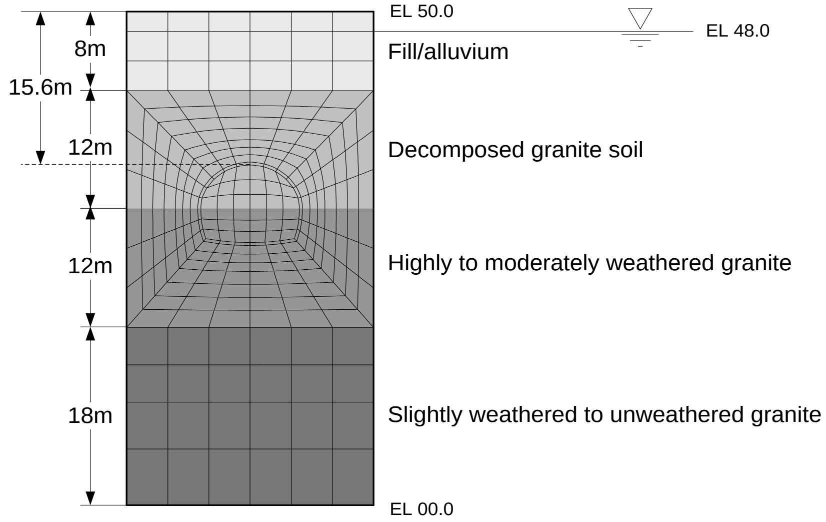


Analysis Model (using MIDASGTS NX)



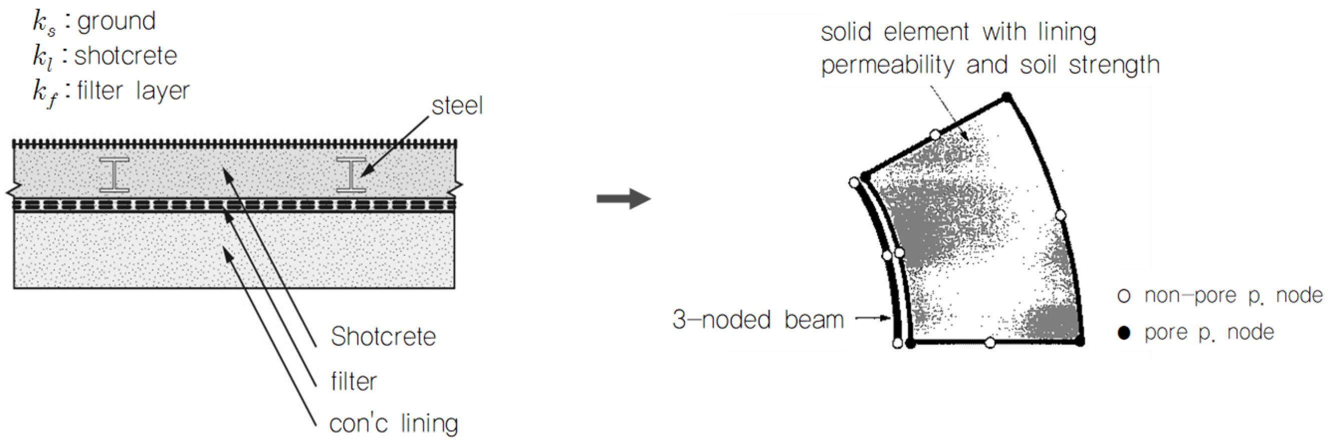




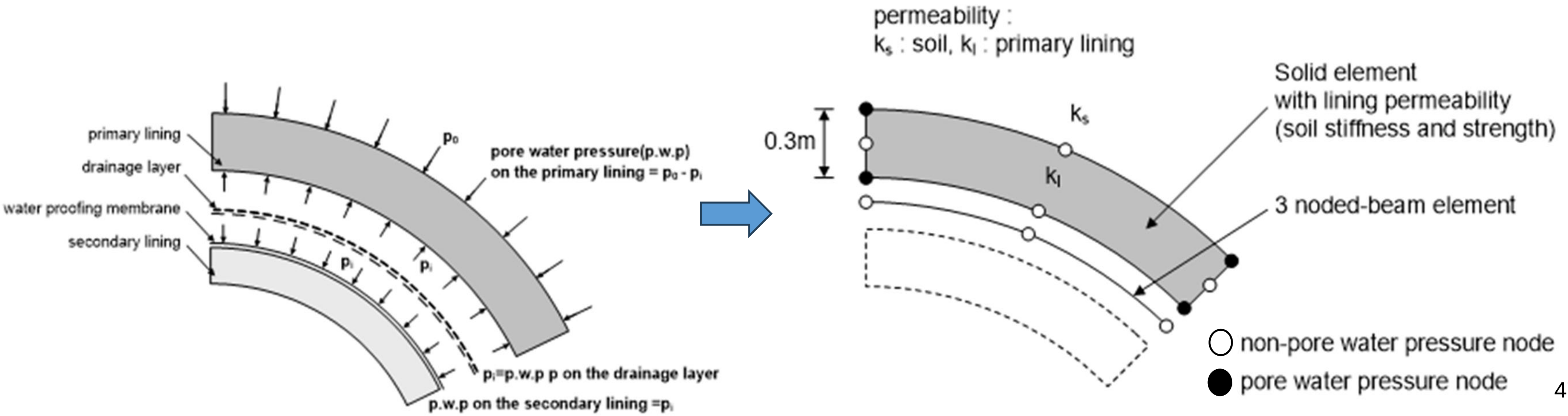


3.4
Long-term Hydraulic Deterioration

Numerical Modelling of Drainage System



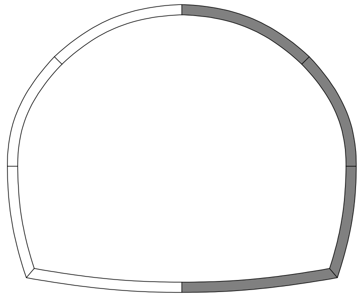
Combined Element Modelling(Shin et al., 2002)



Case A : Partial Clogging of Drainage Layer

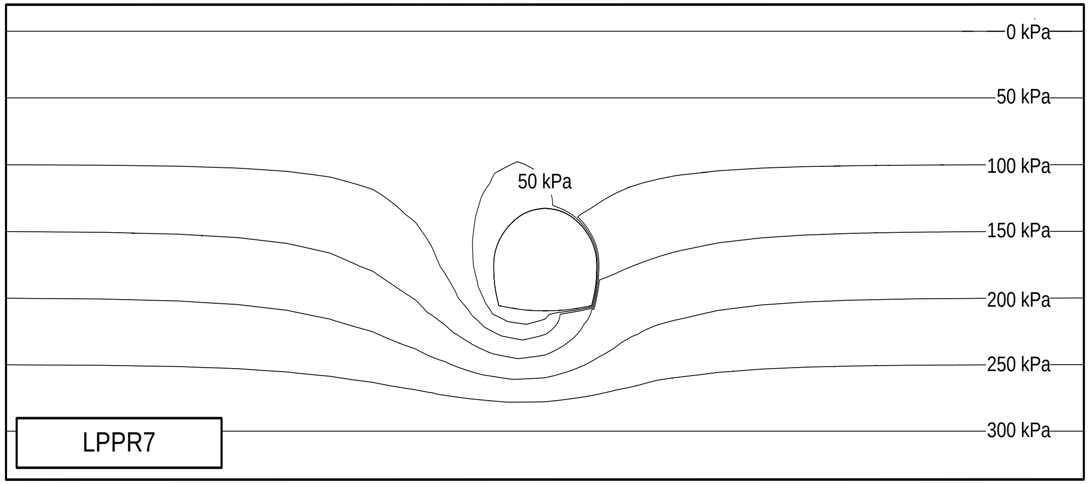
- **Flow behavior around tunnel**

Side wall clogging

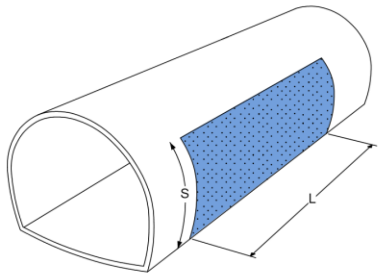


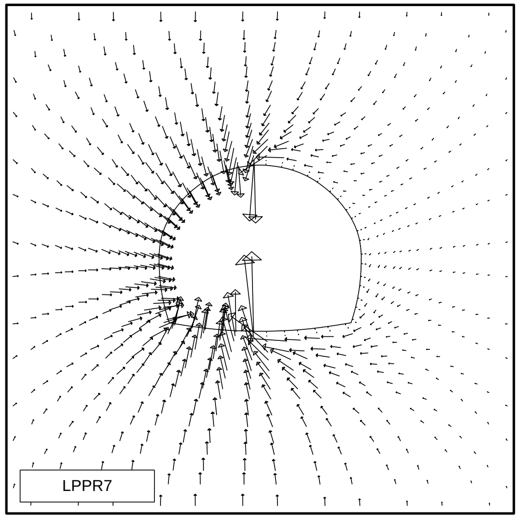
□ Non-Clogged

▬ Clogged



Distribution of pore water pressure

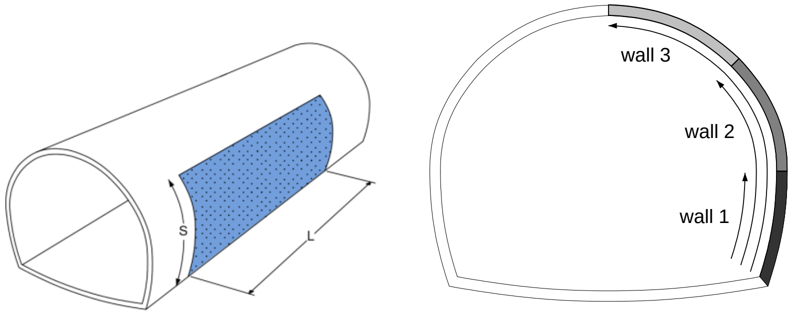


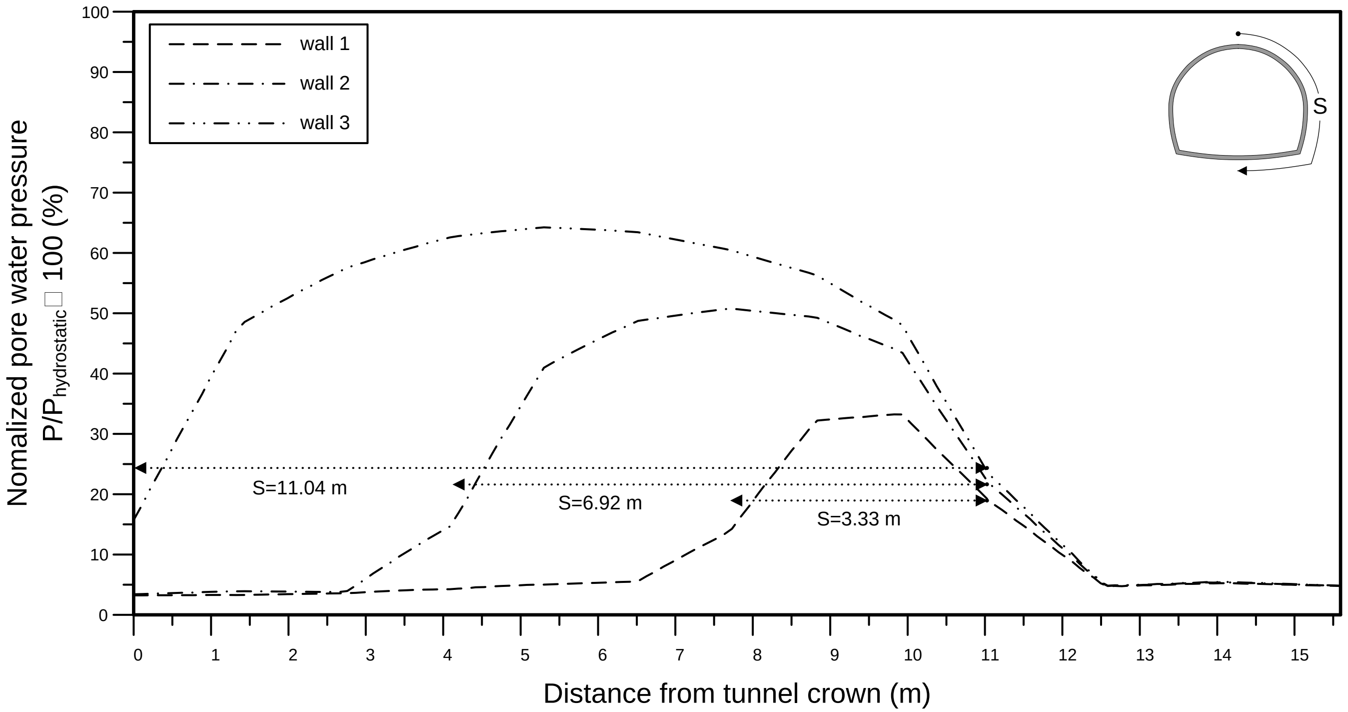


Seepage velocity

3.4
Long-term Hydraulic Deterioration

- **Water Pressure on the lining**

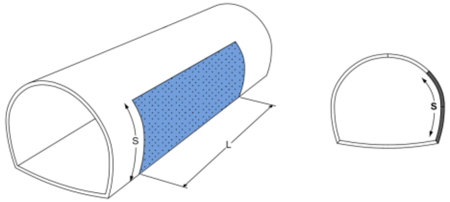




$$\frac{p}{p_o}=\frac{1}{0.49s^2}\left(\frac{p}{p_o}\right)_{\max}(X-0.7s)(X+0.7s)$$

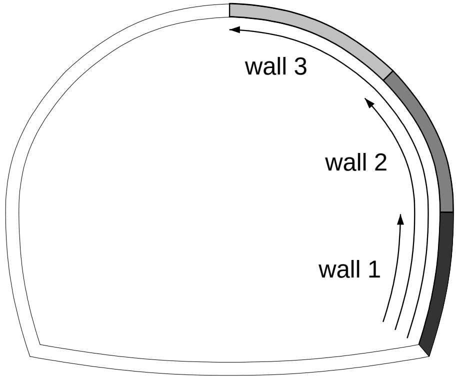
$$\left(\frac{p}{p_o}\right)_{\max}=3.3s+25$$

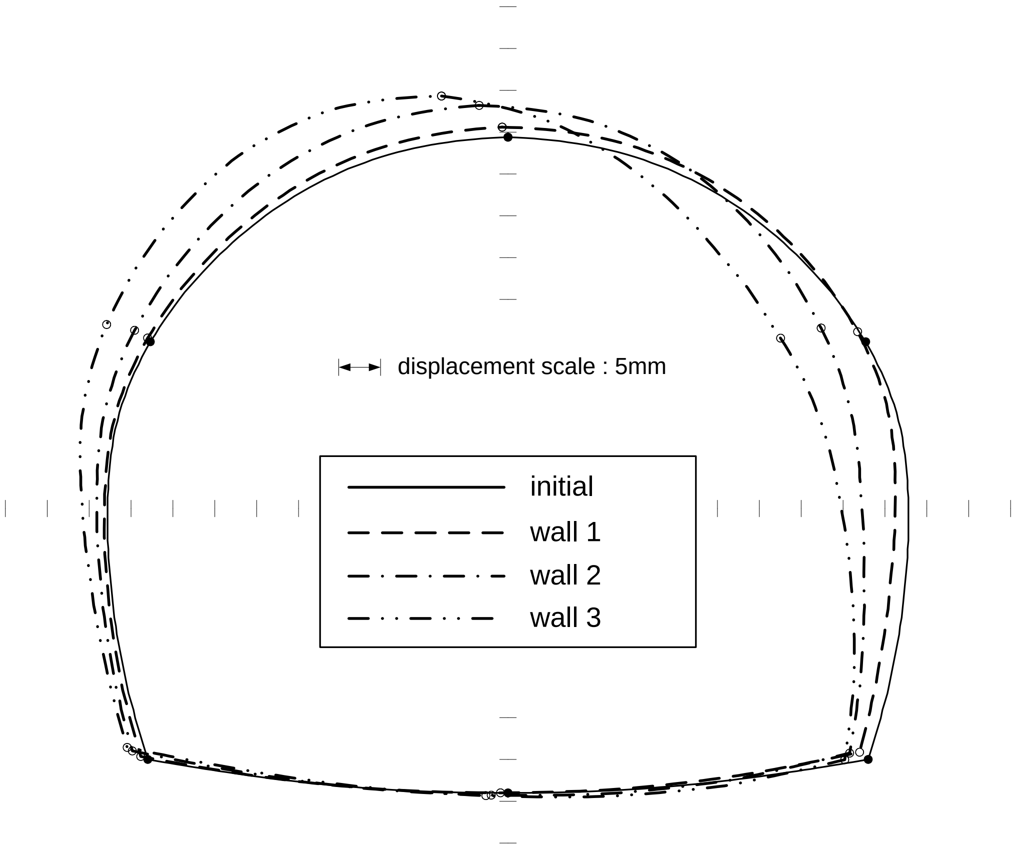
3.4
Long-term Hydraulic Deterioration



- **Lining deformation**

Side wall clogging

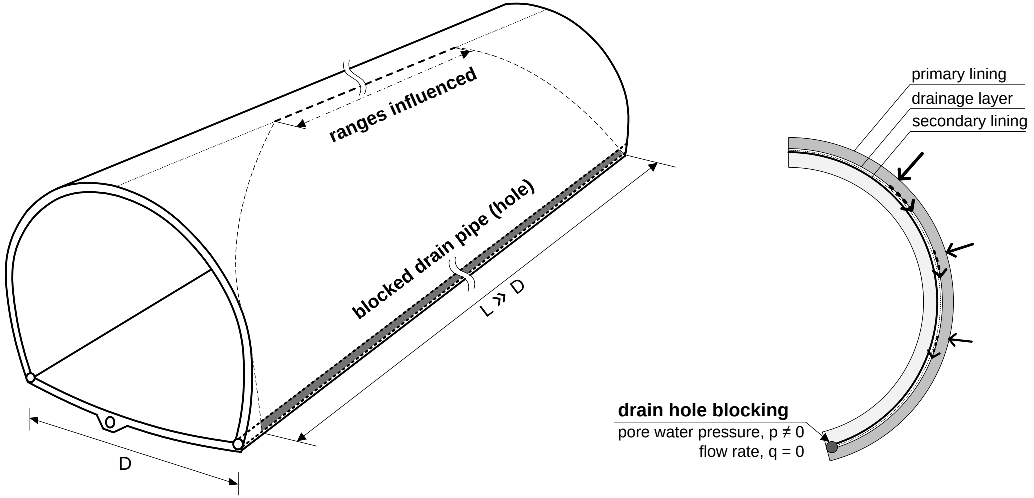




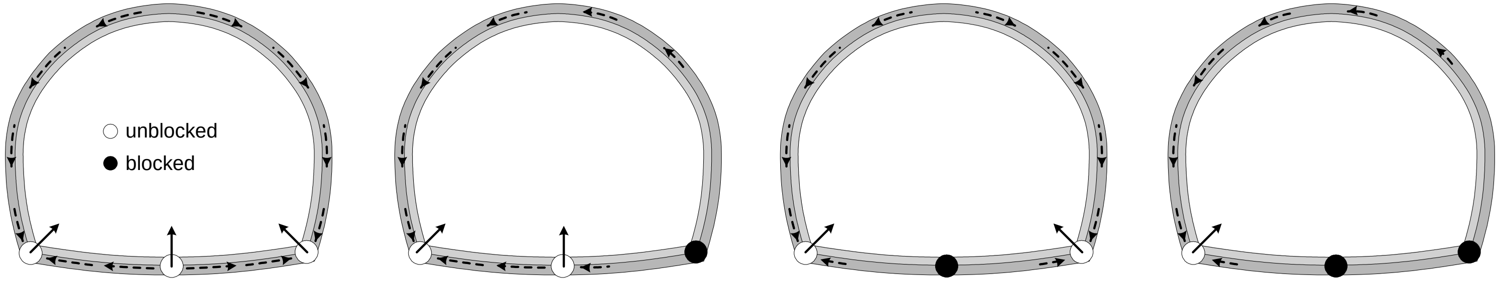
Asymmetric uplift force
causing **tortional behavior**

Case B : Blocking of Drain Holes

- **Drain hole blocking problems in a double-lined structure**



- **Analysis cases for drain-hole blockings ($k_l/k_s = 0.1$; $k_f/k_l = 10$)**



drain-hole free dicharge

right drain-hole blocked

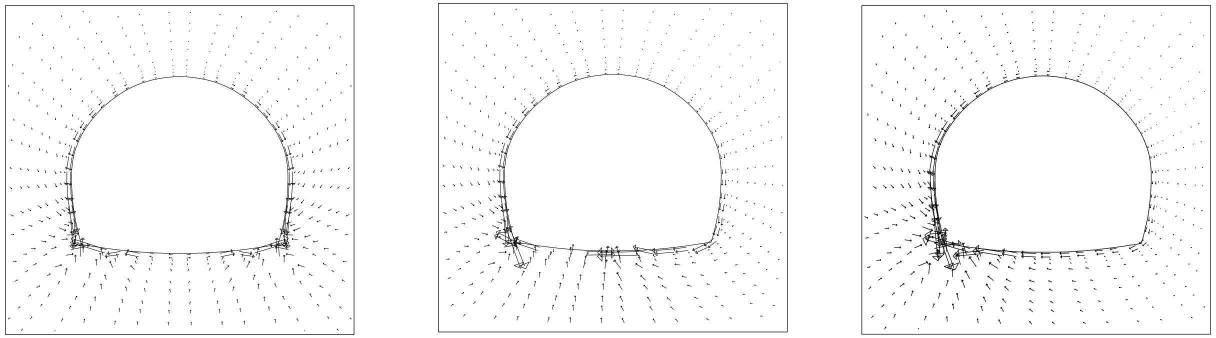
middle drain-hole blocked

right & middle drain holes blocked

3.4
Long-term Hydraulic Deterioration

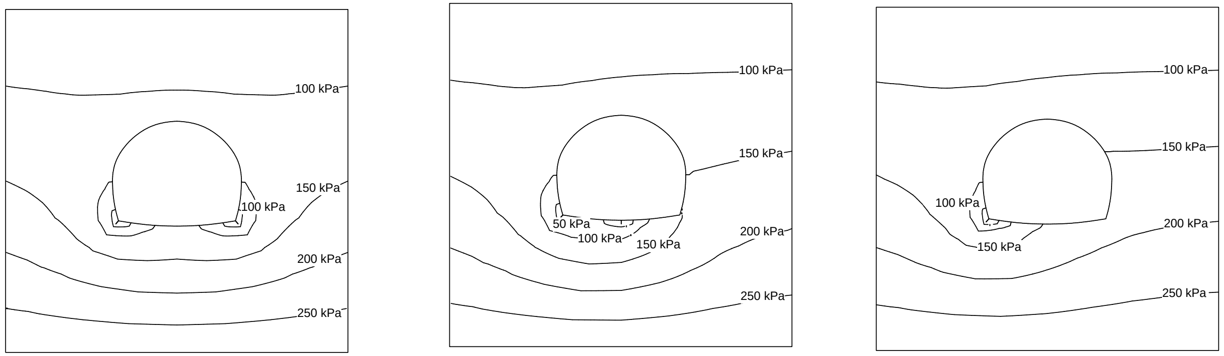
Effect of drain hole blocking

- **Seepage velocity vectors**



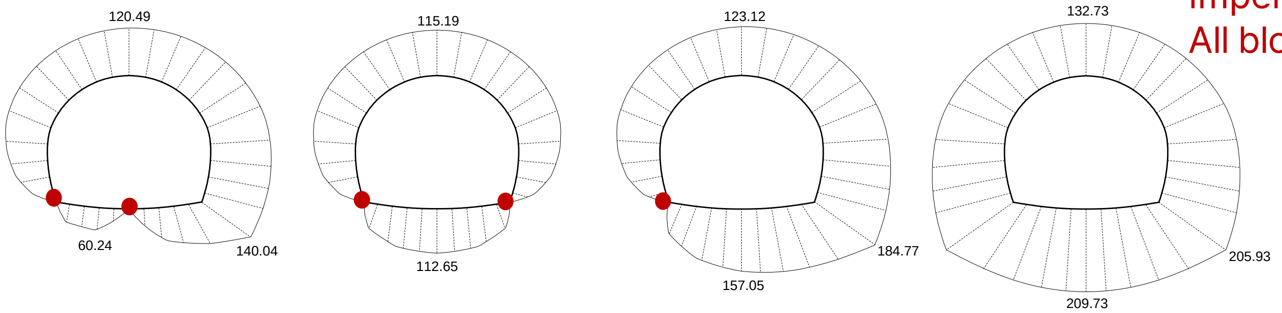
(a) middle drain-hole blocked (b) right drain-hole blocked (c) right & middle drain holes blocked

- **Distribution of pore-water pressure**



(a) middle drain-hole blocked (b) right drain-hole blocked (c) right & middle drain holes blocked

- **Water pressure on the lining**



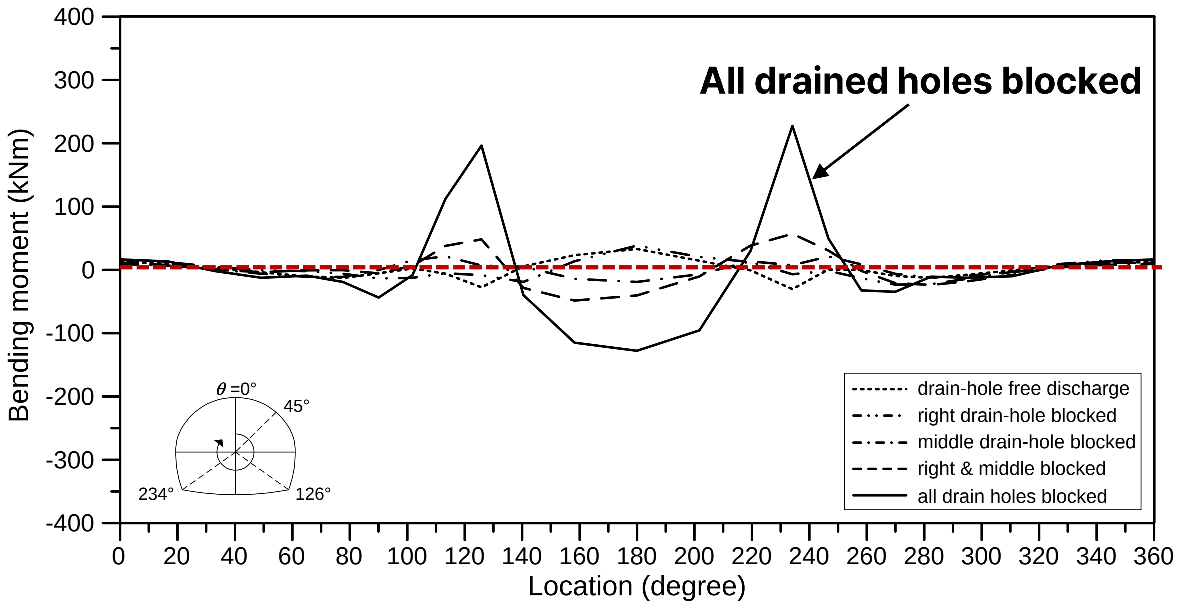
Impermeable
All blocked

① right drain-hole blocked ② middle drain-hole blocked ③ right & middle drain-holes blocked ④ all drain-holes blocked

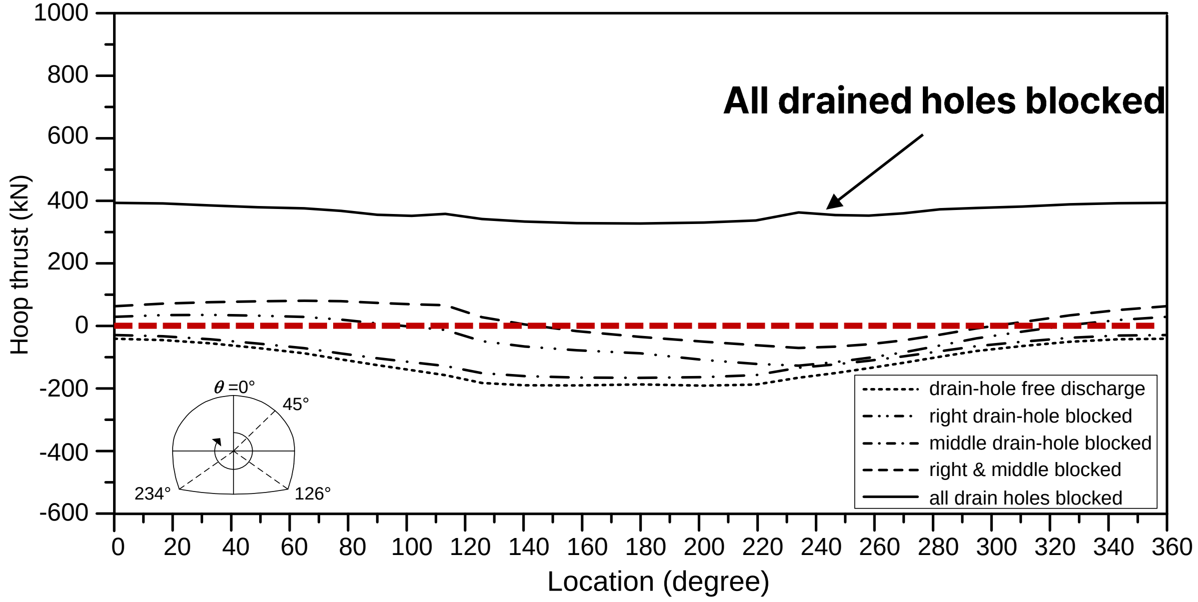
3.4 Long-term Hydraulic Deterioration

Effect of drain hole blocking

- **Bending moments in the linings**


All drained holes blocked

- **Hoop thrusts in the linings**


All drained holes blocked

3.5 Hydraulic Design Considerations

- Drain or Undrain?
- Drained Tunnel
  - inflow rate (free drainage)
  - lowering of groundwater table
  - drainage system and pumping cost
  - P-Q Relationship
    : hydraulic(drainage system) and mechanical(lining) interaction
  - drainage(leakage) control- limited drainage tunnel
  - effects of hydraulic deterioration
- Undrained Tunnel
  - tunnel shape and lining thickness

Site/Structural Measures

4. Hydrological Considerations

in the Design of Underground Structures

지하구조물 설계의 수문학적 고찰

4.1
Hydrological Issues
on the Underground Structures

Damages from the Surface Water to the Underground Structures

- **Flooding**

- **Pressurizing**

Flooded ?

Case 1 : Flooding

Flooding of Tunnel Shaft during Construction of Seoul Metro Line 6
1998.05.02

Flooded Tunnel Shaft

4.1
Hydrological Issues on the Underground Structures

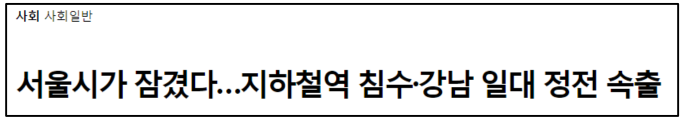
8 Stations of Line 6 flooded through the cross passage connecting Line 7

Flooding through cross passage

Flooding Taereung Station of Seoul Subway Line 7

Case 2 : Flooding of Existing Metro Systems, 2023

Seoul Metro(2023.07.08)



사회 사회일반

서울시가 잠겼다...지하철역 침수·강남 일대 정전 속출

8일 밤 서울 동작구 이수역에 빗물이 유입되고 있다. 연합뉴스

Seoul Metro Network

9 Lines 315km

4.1
Hydrological Issues on the Underground Structures

Jeong Jou Metro, China

2023. 07. 20,   25 Dead

물바다 된 지하철 객실 20일 오후 중국 중부 허난성 정저우에 기록적인 폭우가 내렸다. 이날 운행 중 터널 안에서 갑자기 멈춰 선 지하철 차량에도 많은 빗물이 밀려들어 승객 어깨 높이까지 차올랐다(왼쪽 사진). 차량을 빠져나온 승객들이 구조대의 도움을 받아 대피하고 있다. 유튜브 화면 캡처

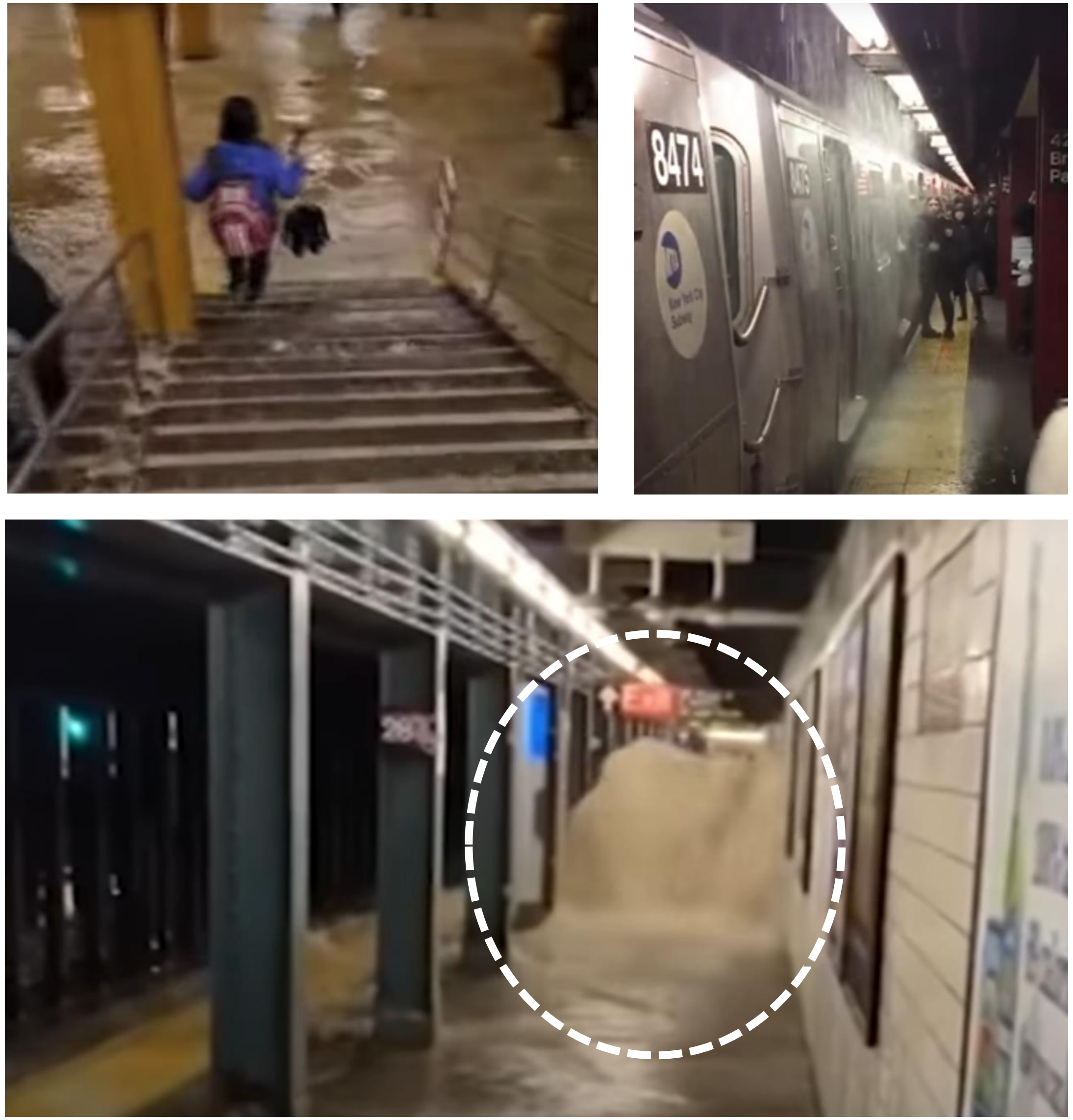
4.1

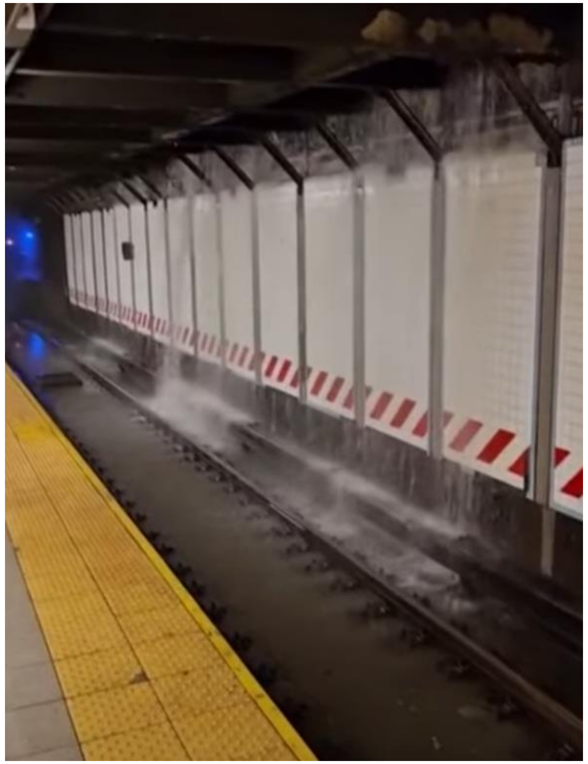
Hydrological Issues on the Underground Structures

Flooded Jeong Jou Metro

지난 20일 중국 허난성 정저우 지하철 객실 내 침수 장면

New York Metro, USA (2023.09.29)





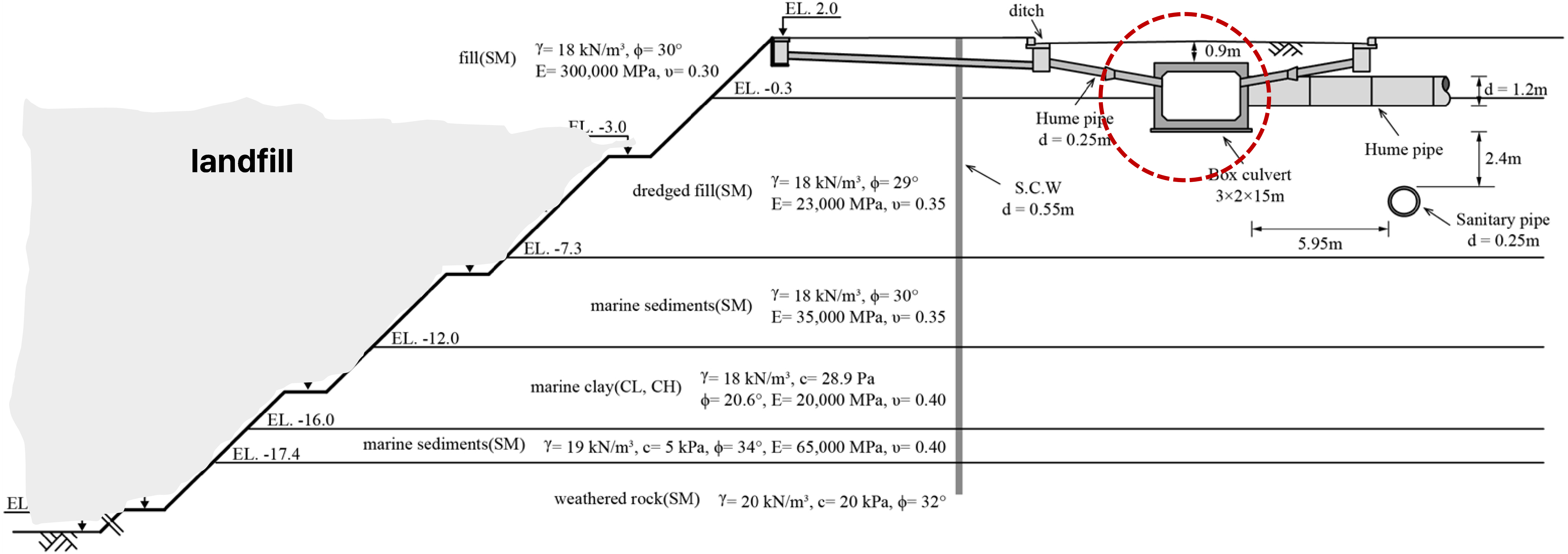
2021.09.02

Case 3 : Pressurizing

Uplifted manhole cover
2023.8.10 창원

Failure of storm sewer system

Box Culvert
3m x 2m

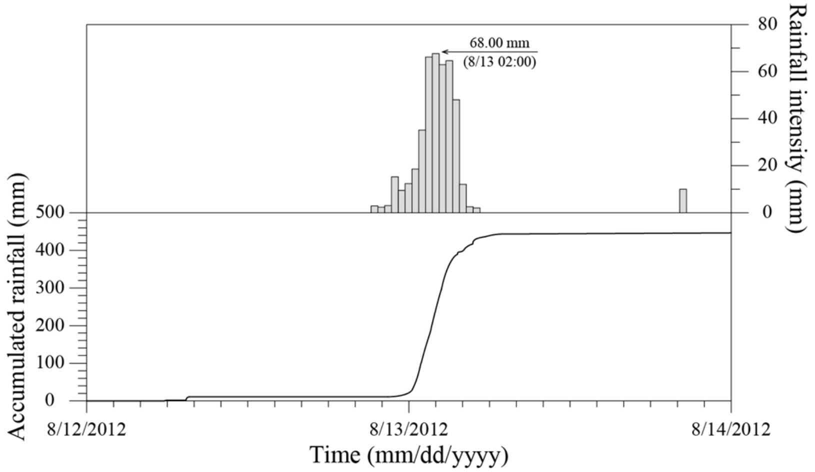


Storm sewer profile

4.1
Hydrological Issues on the Underground Structures

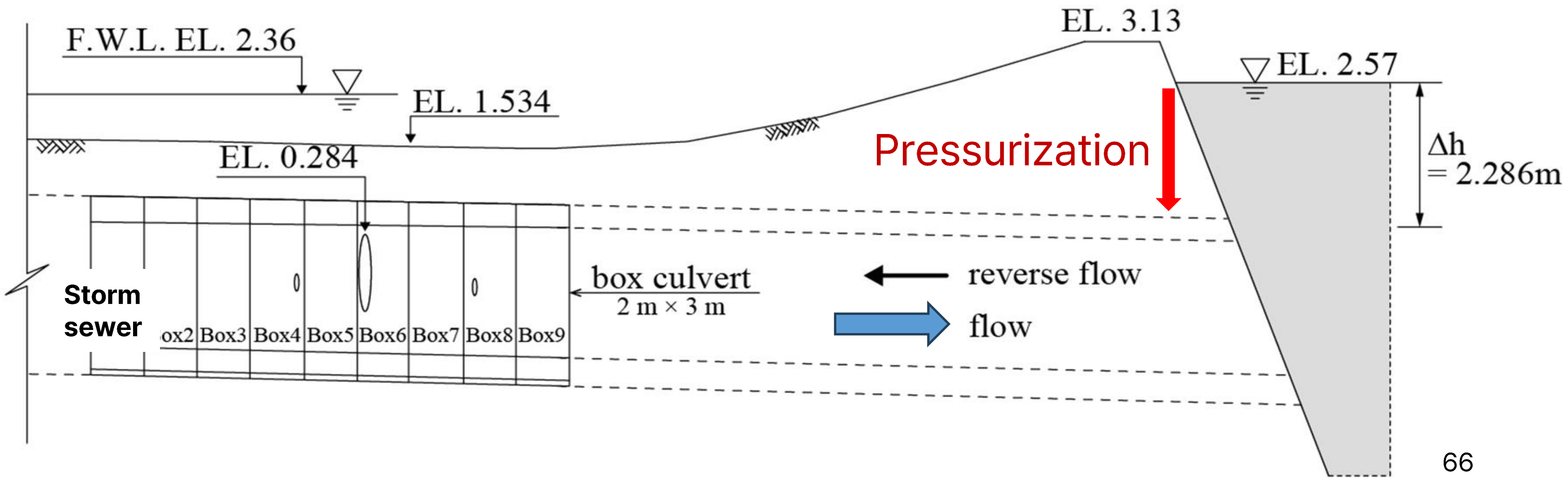
Pressurizing mechanism

- **Recorded rainfall**
  (2012.08.12)



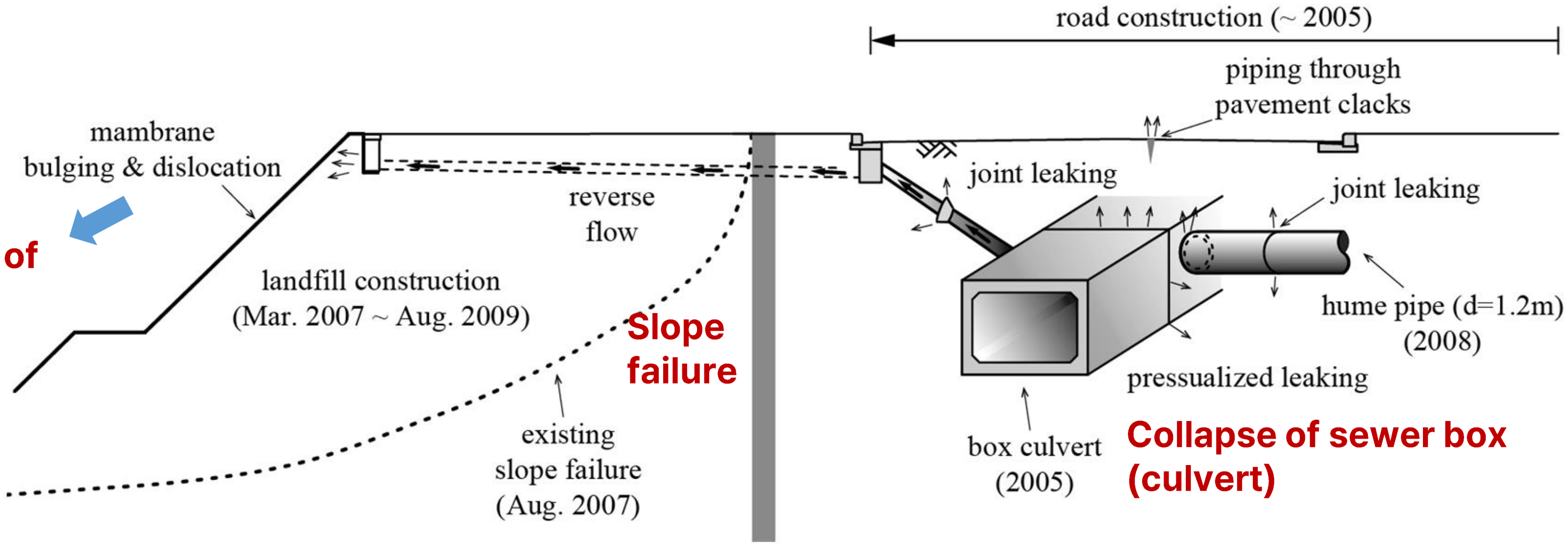
Hydrological Analysis and Pressurization Mechanism

- **Pressurizing and backwater flow**



Reconstructed water levels in the storm sewer system

Sewer Collapse → Slope Failure → Flooding of Landfill



Flooding of landfill

Slope failure

Collapse of sewer box (culvert)

4.2
Surface Water Management
for the Underground Structures

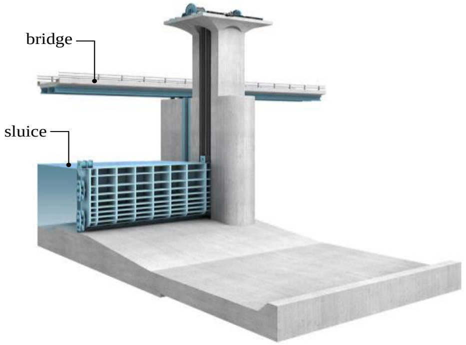
Surface Water Management
Control of Flood and Pressurization

- **Out-of-tunnel Measures : Runoff Control**

  Store or Diverse?

  Active Measures Based on Hydrological Study

  ⇨ Land or Urban Planning



- **In-tunnel Measures**

  Blocking or Protecting?

  Passive Measures based on Hydrlogical Study

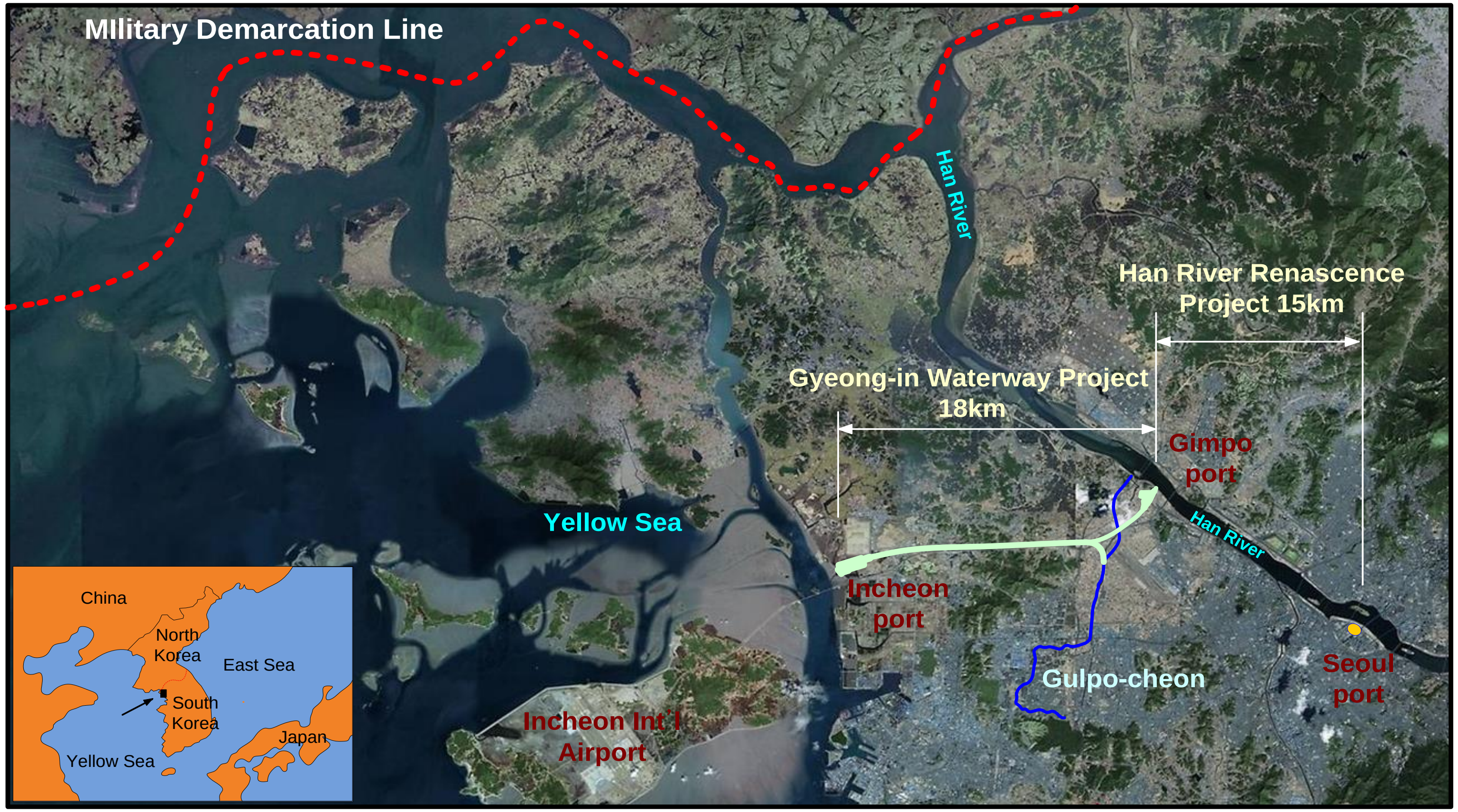
  ⇨ Structural Design

Out-of-Tunnel Measures : Runoff Control

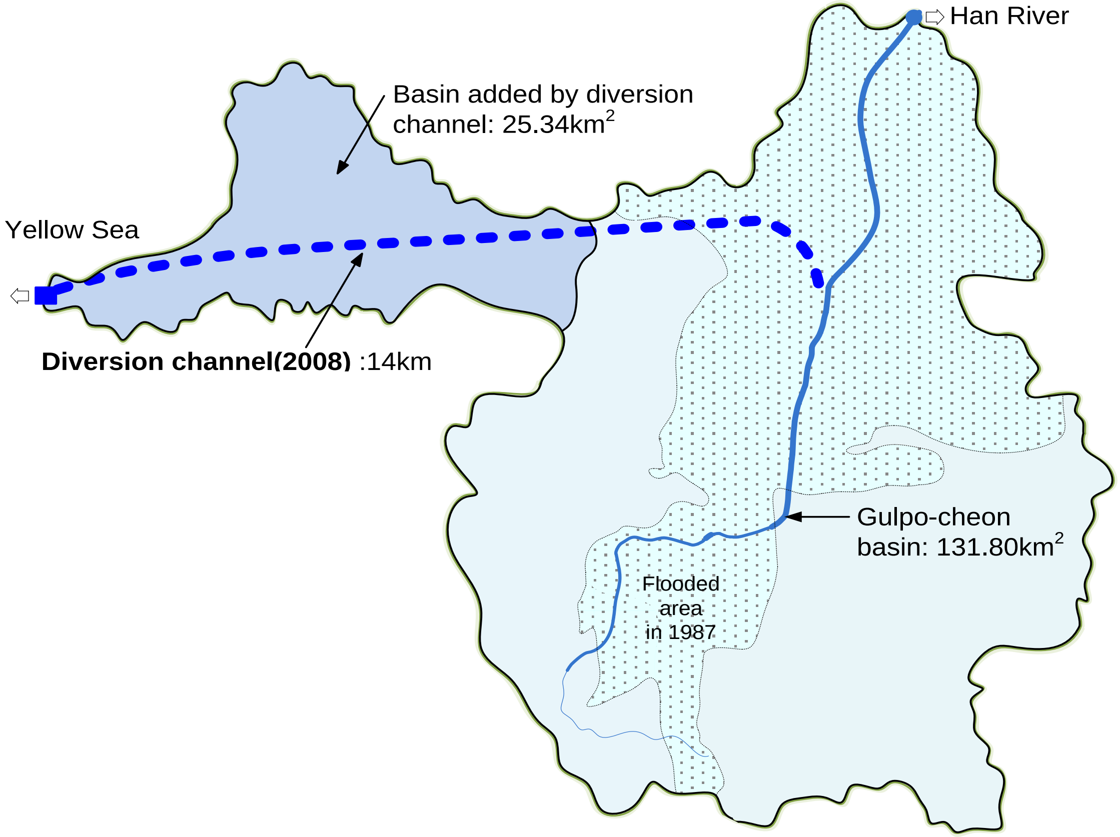
Example Cases of Runoff Control

Case 1: Open Diversion Channel

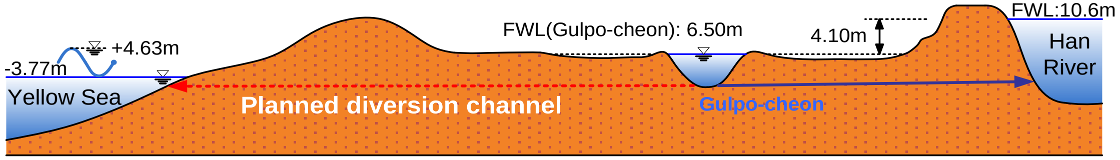
The Gyeong In Multi-purpose Waterway Project



The Gyeong In Multi-purpose Waterway Project



Flooding in 1987



Diversion Channel in 1992-2008

The Gyeong In Multi-purpose Waterway Project

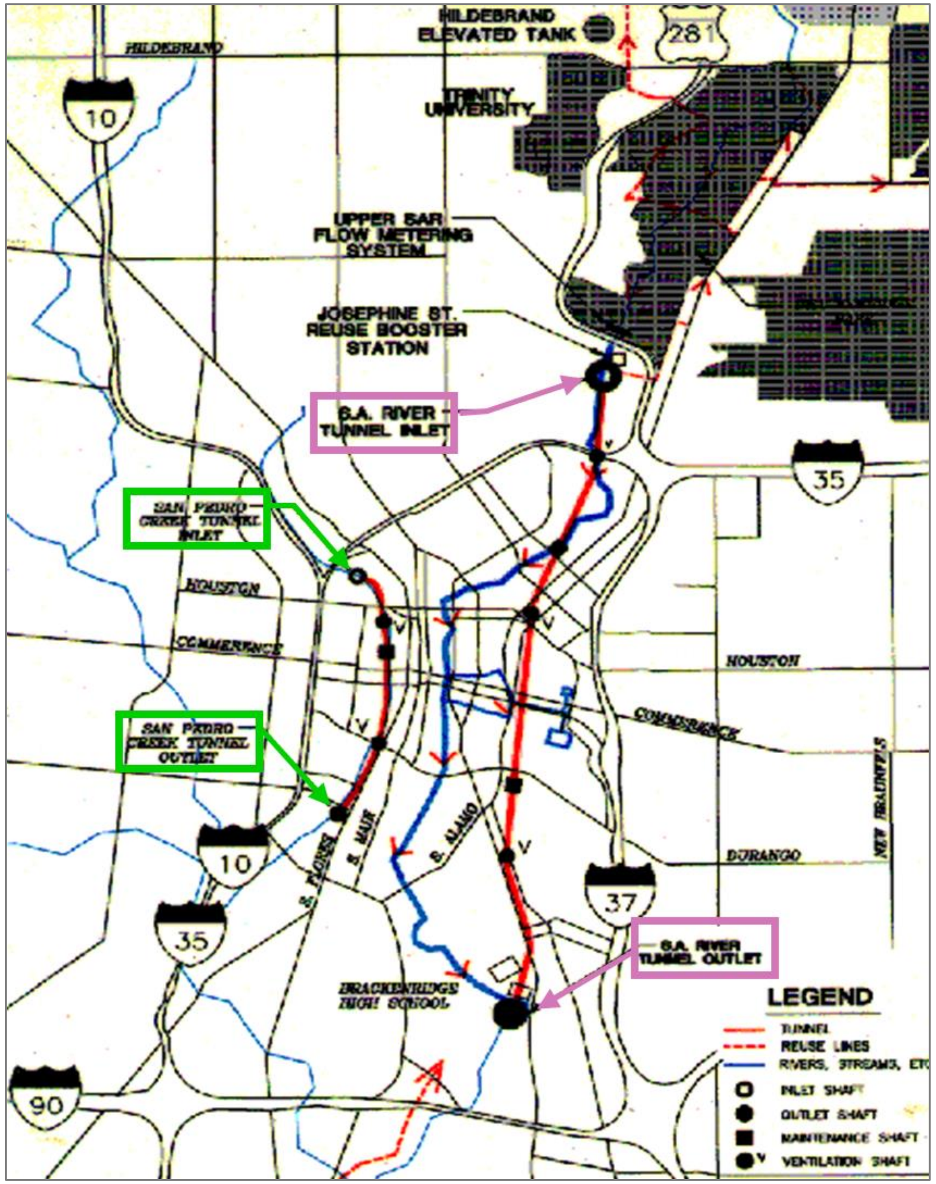
4.2
Surface Water Management
for the Underground Structures

Case 2: Diversion Tunnel

San Antonio City
Texas, USA

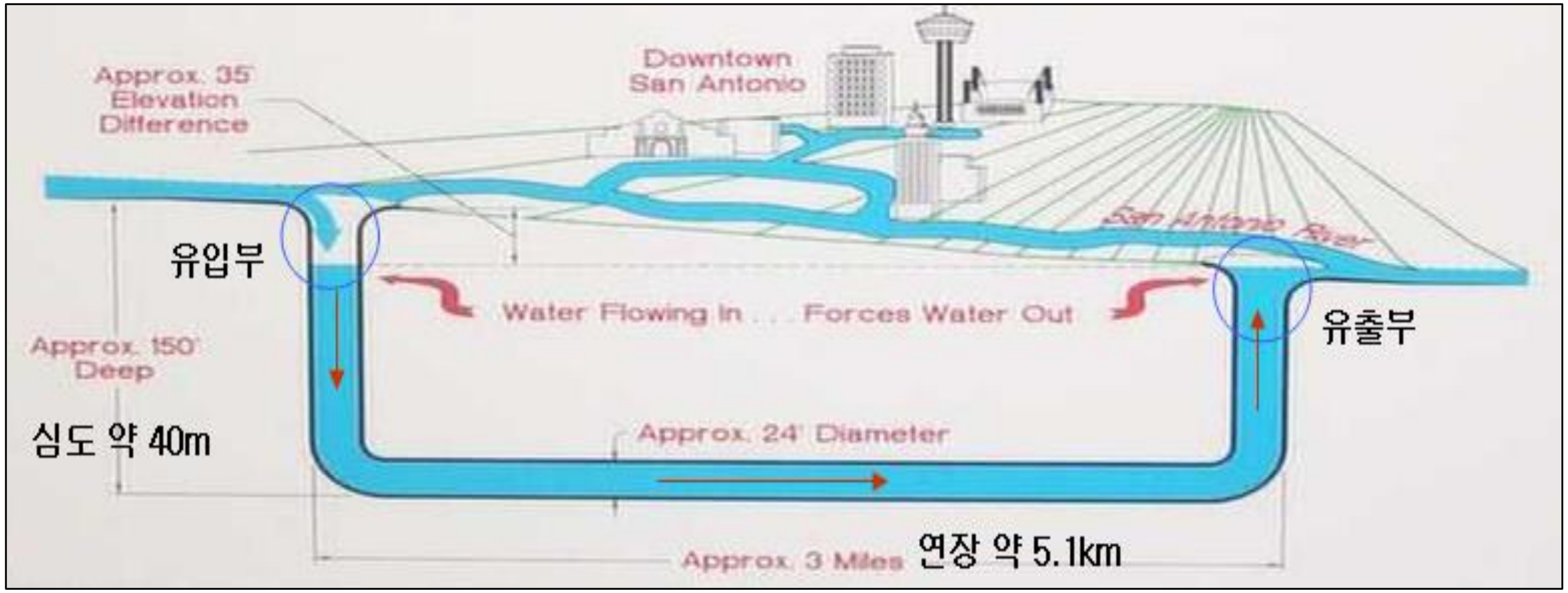
San Antonio River Tunnel
: 5.0 km, D=7.2m

San Pedro Creek Tunnel
: 1.8km



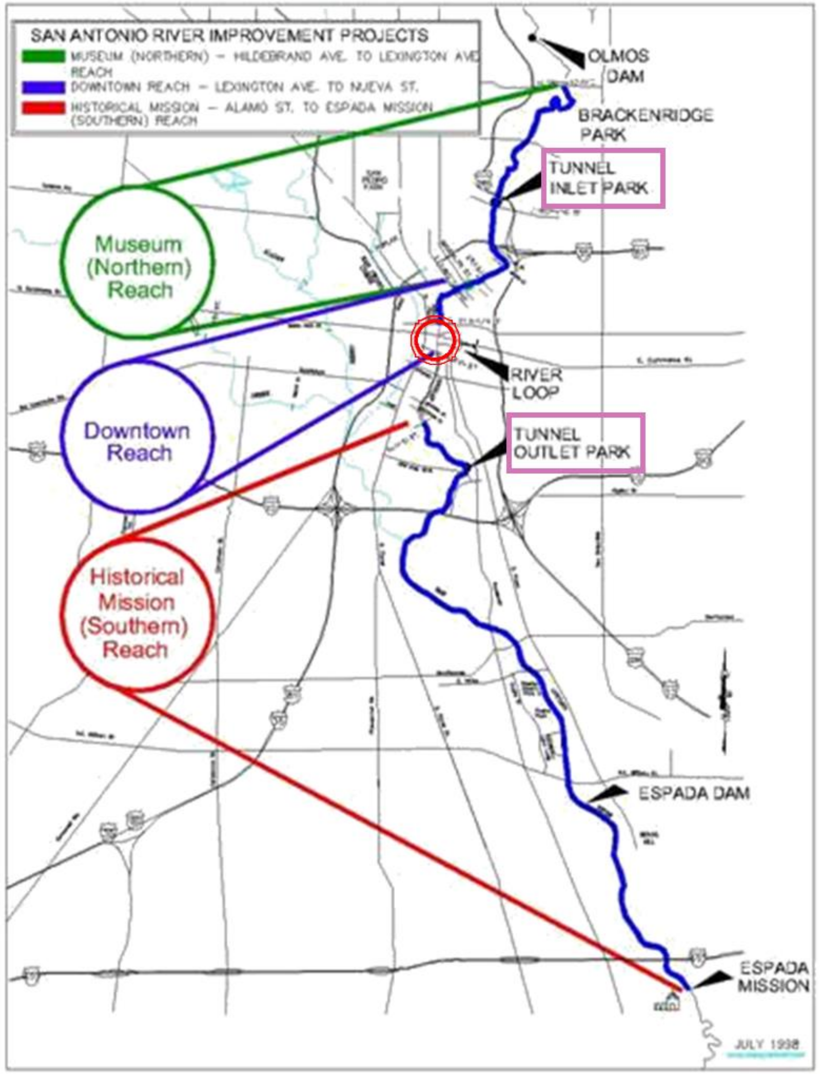
San Antonio River Tunnel

San Antonio City, Texas, USA
Water way tunnel : L=5 km, D=7.2 m, H=40 m

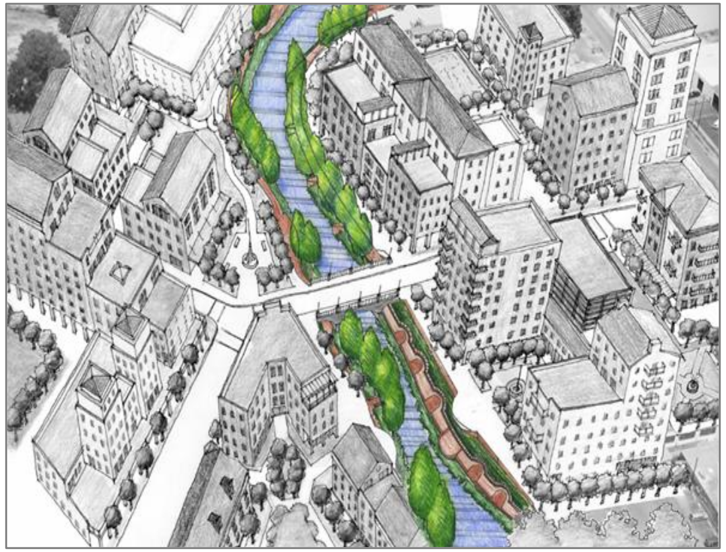


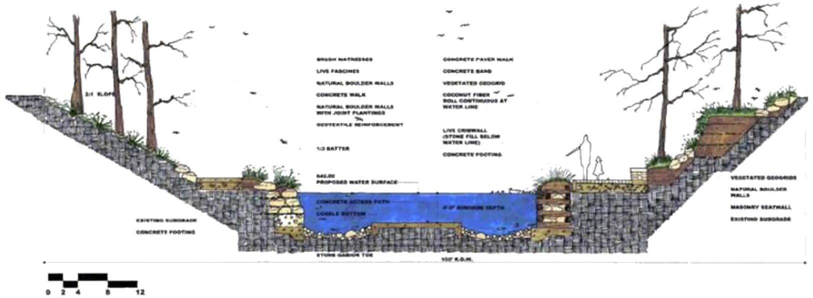
4.2
Surface Water Management
for the Underground Structures

San Antonio Stream Bank Restoration



Length : 13mile(20km)
(including 5 km tunnel)





BIO-ENGINEERED STREAMBANK RESTORATION

Case 3: Storm Water Storage Tunnel

Shin wall Water Storage Tunnel, Seoul

L=4.7km
D=10m
V=320,000t

서울 양천구 신월빗물저류배수시설

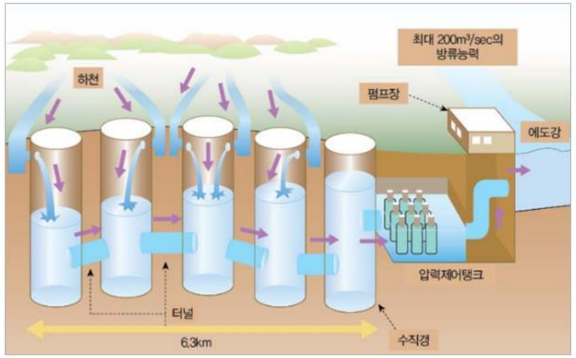
최대 처리 용량	시간당 95~100mm
저류 용량	32만t
배수관 지름	10m
사업비	1390억원
완공	2020

자료

서울 양천구 신월빗물저류배수시설

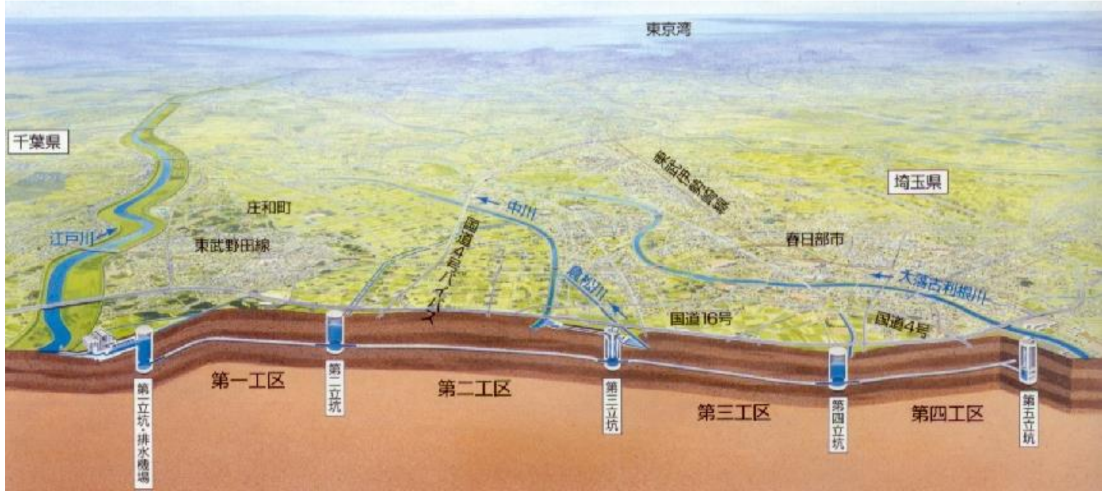
4.2
Surface Water Management
for the Underground Structures

Storm Water Storage Tunnel in Tokyo, Japan



Operation Scheme

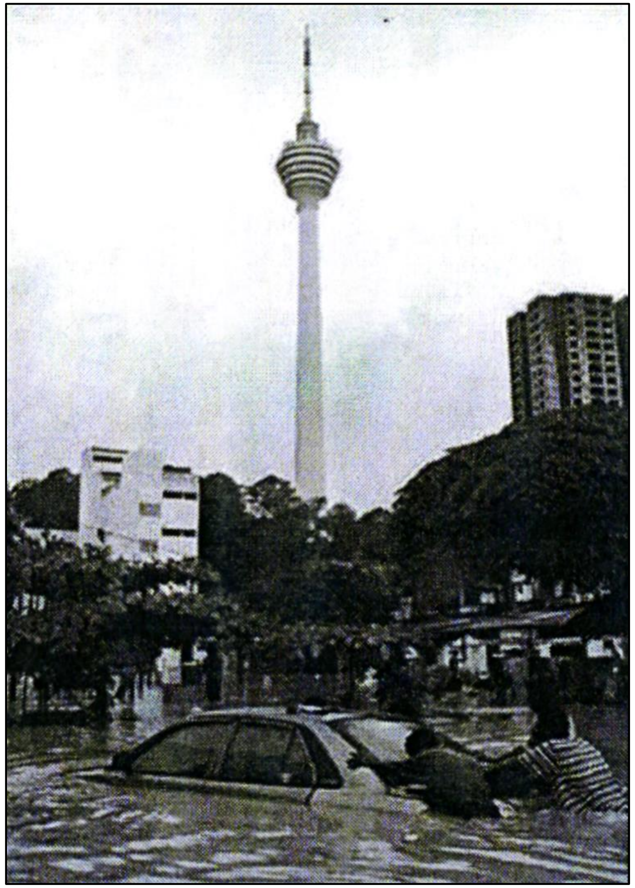
Beneath the Tokyo Circle Road Line 7
- Length : 4.5km
- D= 12.3m
- H= 40m



Beneath the Tokyo Metropolitan Highway
- Length = 6.3km
- D=10.6m
- H=50m

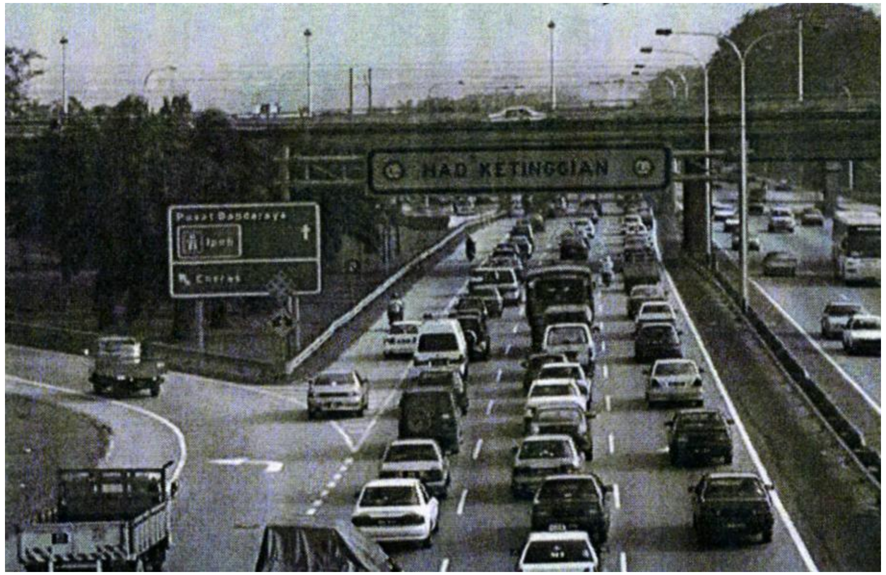
Case 4: Multi-disciplinary Diversion Tunnel

SMART Project
Kuala Lumpur, Malaysia



Floods

Traffic congestion

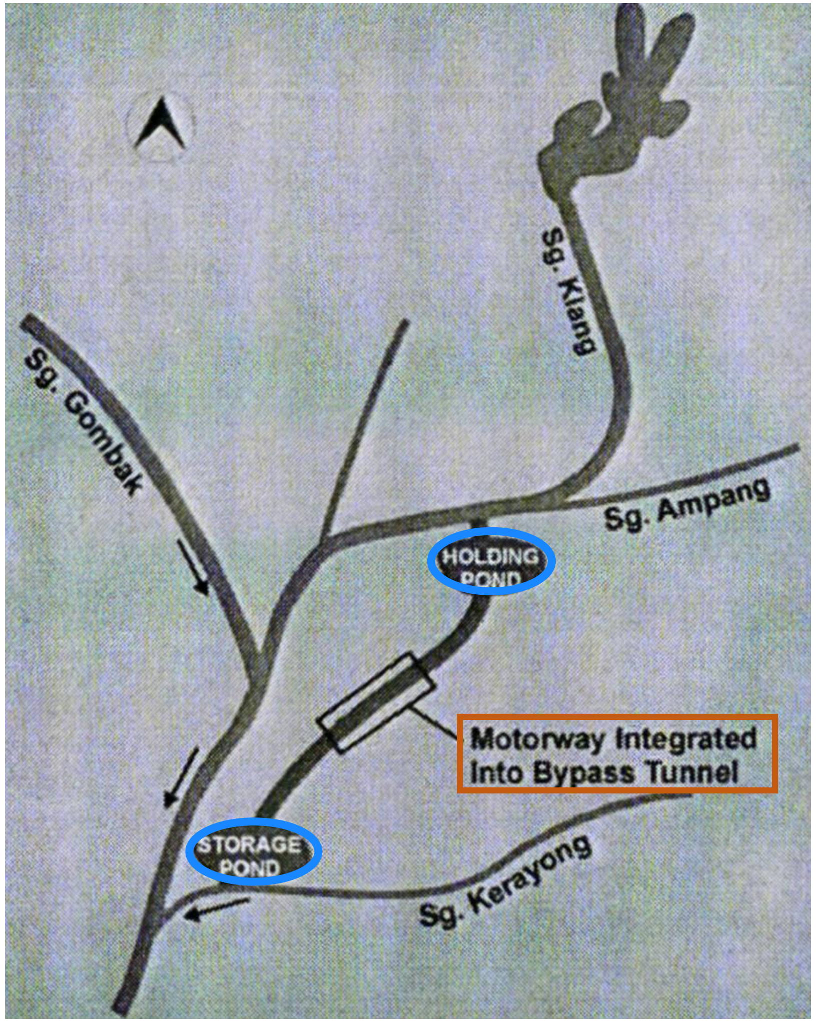


- 2001.07: competition for solution
- 2002.04: start detailed design
- 2003.01: start construction
- 2007.05: Opening of road tunnel
- 2007.09: Acceptance of stormwater tunnel

4.2
Surface Water Management for the Underground Structures

SMART Project

Stormwater Management and Road Tunnel



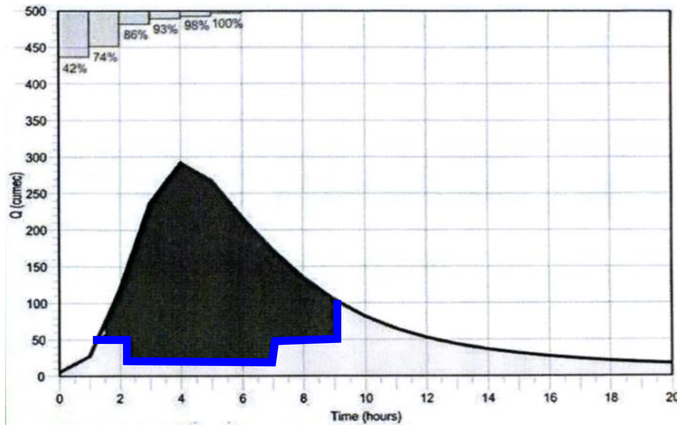
Stormwater management
Diversion Arrangement

- 280m3/s flood relief tunnel
- 9km bored tunnel
- D_i=11.8m, D_o=13.26m
- Twin level 2 lane highway
- Intake structures
- 2 ponds
- 4 ventilation shafts

(Double deck, Slurry TBM)

4.2
Surface Water Management for the Underground Structures

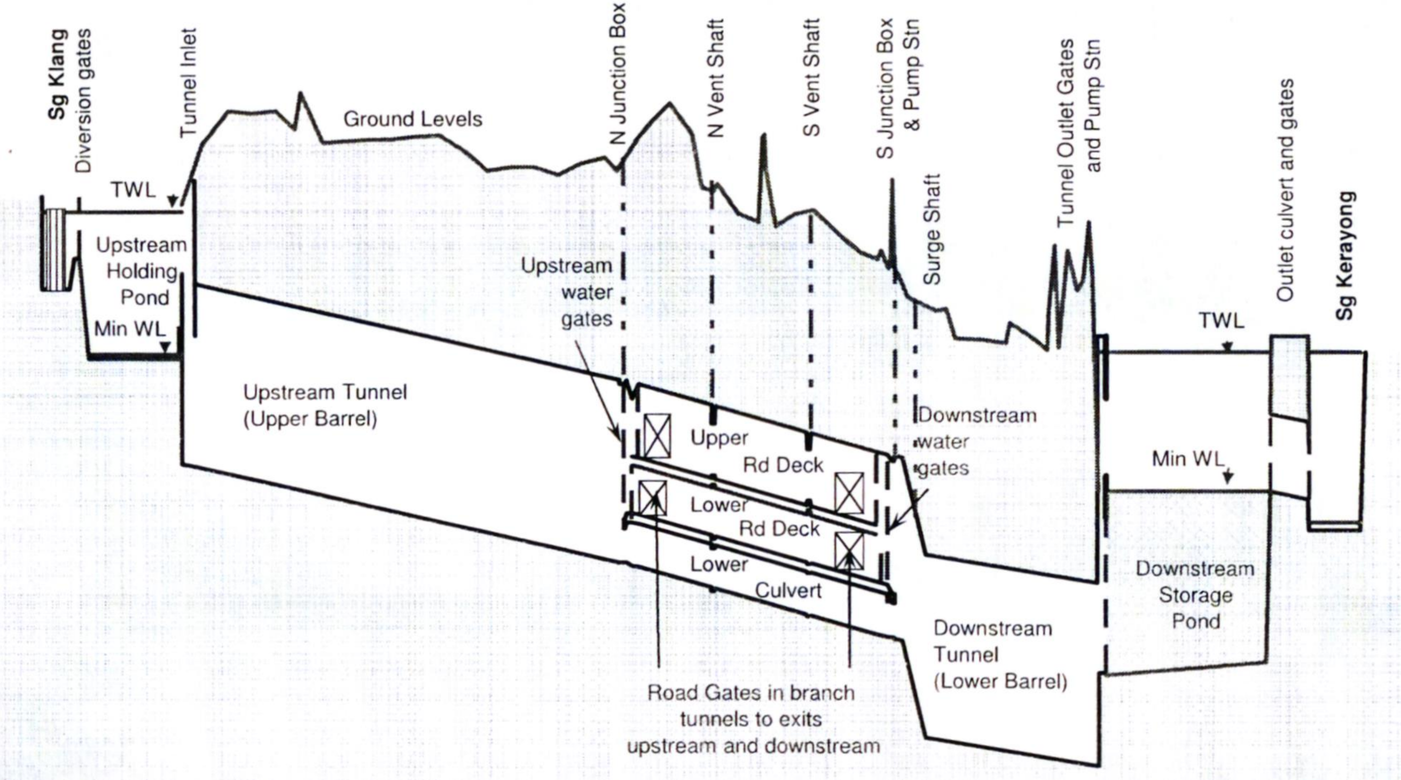
SMART Project



Design Hydrographs : q_{100} 6 hours storm

- Inlet(hold) pond : 0.6 M cum
- Tunnel : 1.0 M cum
- Outlet(storage) pond : 1.4 M cum

Longitudinal section



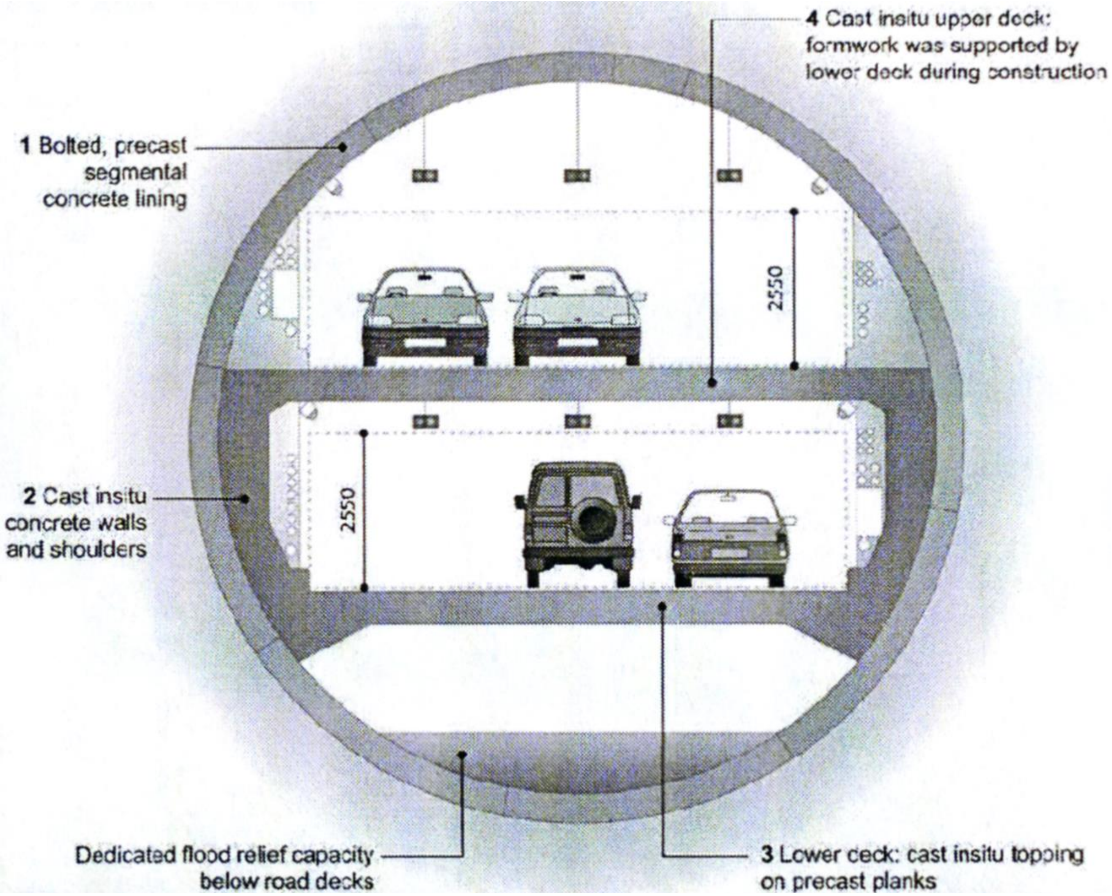
SMART Project

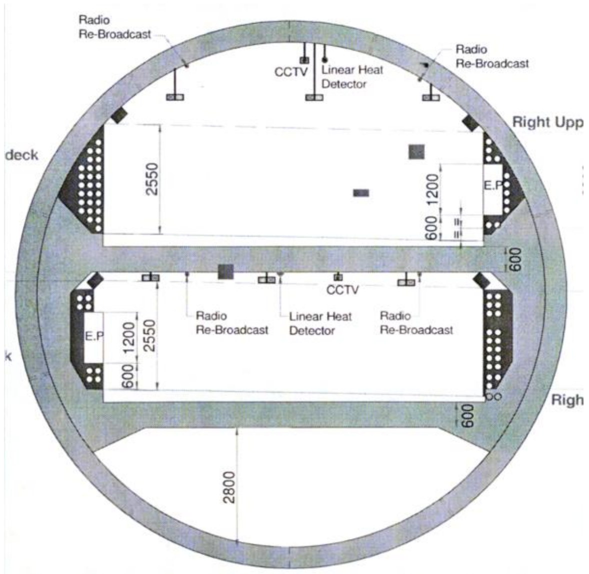
Highway Arrangement

Central 3.0km highway tunnel
- upper and lower decks
- 2x3.35m lanes
- emergency lane

Design speed 60km/hr
- indicated speed 50km/hr

Headroom 2.5m
- cars only
- 10MW fire road



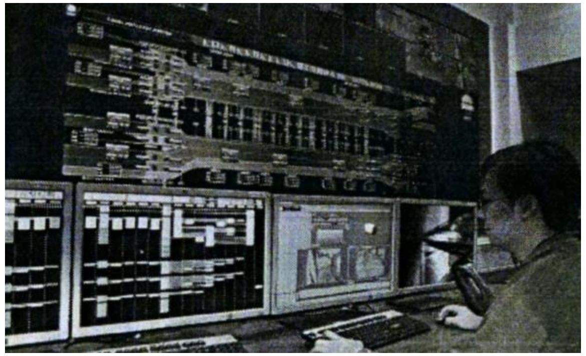


Service layout

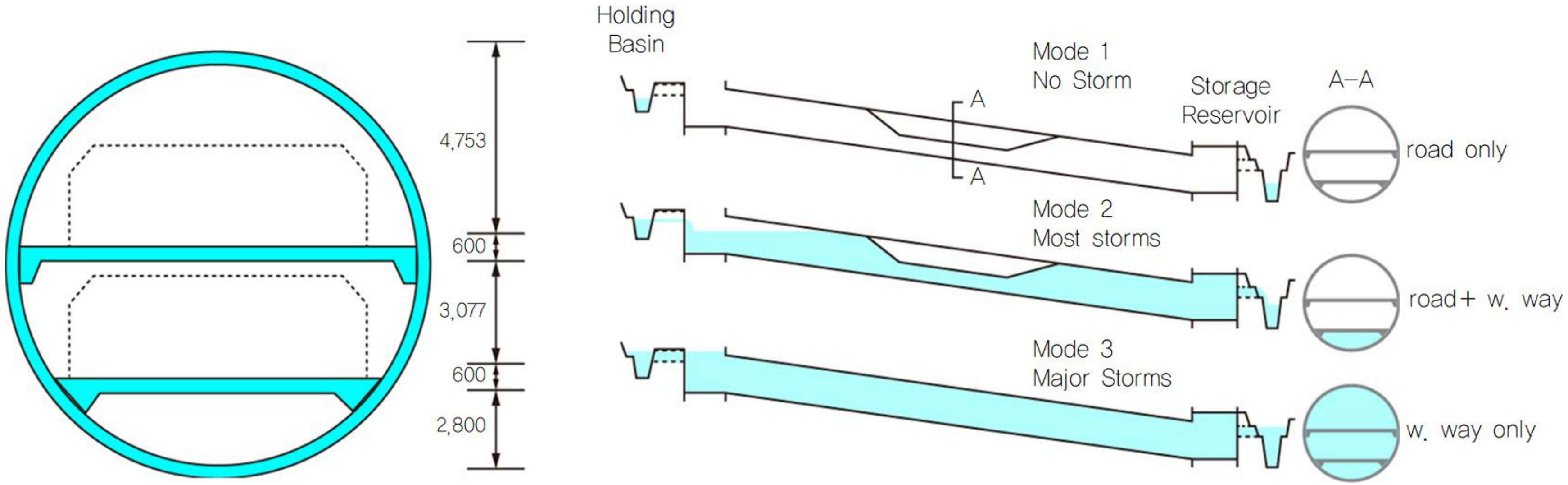
4.2
Surface Water Management for the Underground Structures

SMART Project

Operational control



Operation Modes



SMART Project(Stormwater Management And Road Tunnel), Kuala Lumpur, Malaysia
(D_o: 13.26m, Slurry TBM, Double Deck Tunnel)

In-Tunnel Measures

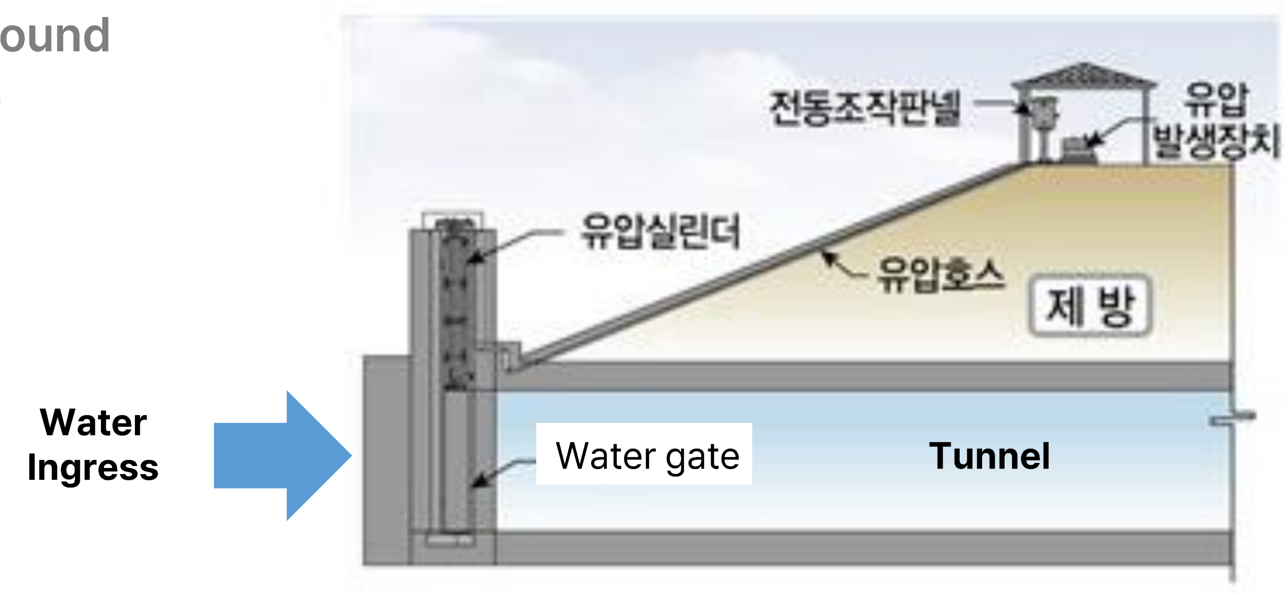
Case 1 : Entrance Water Barrier

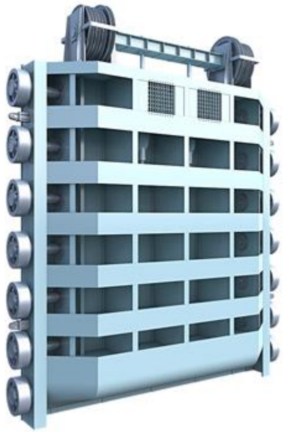
Flood Protection for the Underground Structures

Entrance water barrier of Seoul Metro

Case 2: In-tunnel Flood Control System

- **Flood Control Gates in Tunnels**





Water gate

Flip gate

- **Possibles Locations of Water Gates in the Tunnel**
  - river crossings
  - cross passage between metro Lines
  - sub river, subsea tunnels
  - emergency barriers

4.2
Surface Water Management for the Underground Structures

Large-scale inflatable structures for tunnel protection: a review of the Resilient Tunnel Plug project

Eduardo M. Sosa, Gregory J. Thompson, Gregory M. Holter & John M. Fortune

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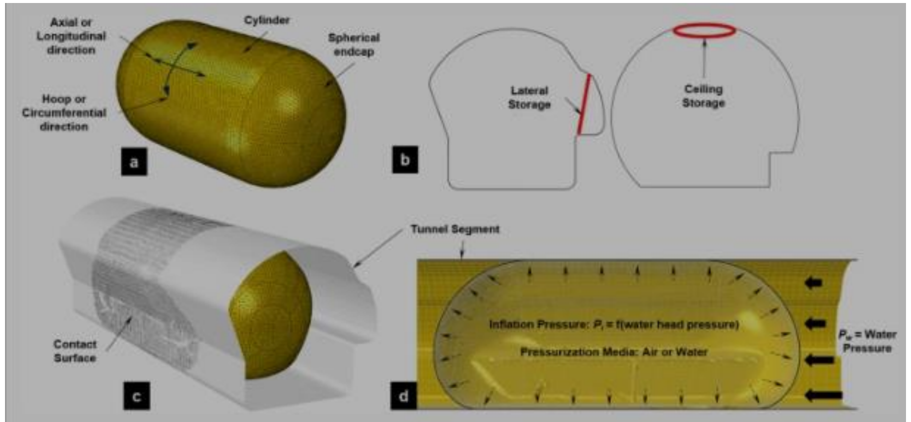
- ## Air Inflating System



A conceptual overview of the RTP System: **a** Inflatable plug, unconfined configuration; **b** Tunnel profiles and folded plug storage areas; **c** Inflatable plug deployed and inflated in the tunnel (confined configuration); **d** Longitudinal cross-section, inflation and flooding pressures [42,43,44,45,46,47]

Phase 2b, full-scale testing, and three-layer Vectran plug. Deployment and low-pressure air inflation for the initial positioning of the plug before flooding simulation

Giant Tunnel Plug

4.3 Hydrological Design Considerations

- **Floodings**
  - store, diverse, or blocking ?

- **Pressurizing**

Measures

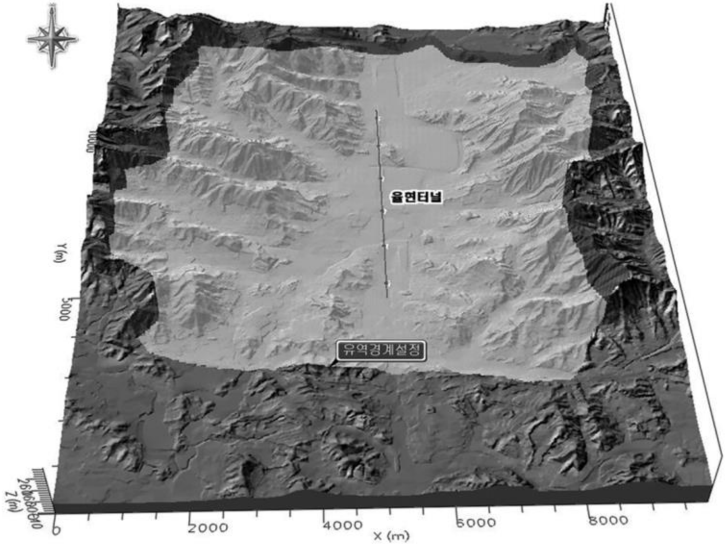
- **Out-of-tunnel Measures : Regional/land/Urban Planning Aspects**
  - stormwater storage tunnel
  - bypass(diversion) tunnel
  - multi-purpose tunnel
- **In-tunnel Measures : Site/ Structural Design**
  - portal or in-tunnel water gate
  - inflating system

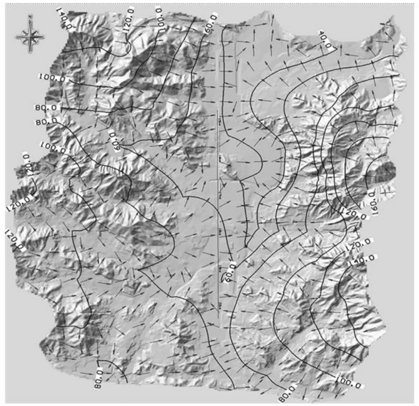
5. Concluding Remarks

5. Concluding Remarks

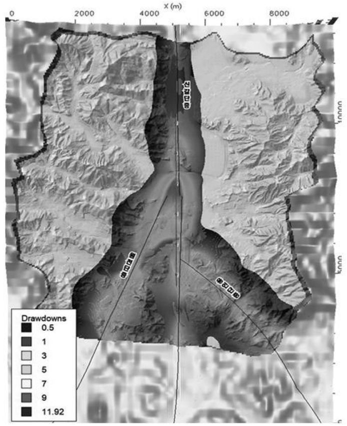
First Step : Identification of Hydraulic and Hydrological Risk(issues)

Regional Hydrological Analysis for the Catchment Area





Flow Vectors



Lowering of Groundwater Table

- **Hydrological Risks**
  - flooding
  - pressurizing

  → Protection: land/urban planning

- **Hydraulic Risks**
  - high inflow rate
  - high water pressure
  - hydraulic deterioration

  → Resist hydraulic impacts

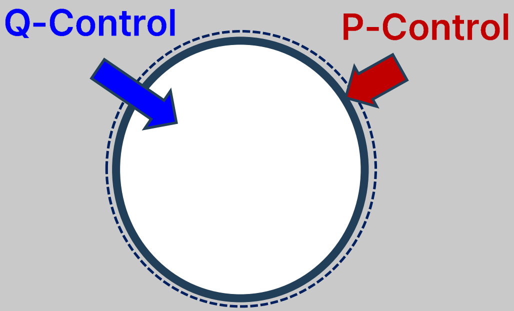
- **Hydraulic Environmental Risks**
  - lowering of groundwater table

  → Drainage control

5.
Concluding Remarks

Principle

Problem of
P-Control, or
Q-Control



Hydraulic and Hydrological Considerations

- **Surface Water: Hydrological Control**

  Store, Diverse or Blocking ?

  - Storage tunnel **(Q control)**
  - Open or diversion tunnel **(Q control)**
  - Water gates **(P control)**

  ➡ **Macro scale, Land/Urban Planning Measures**

- **Groundwater: Hydraulic Control**

  Drained, Limited, or Undrained?

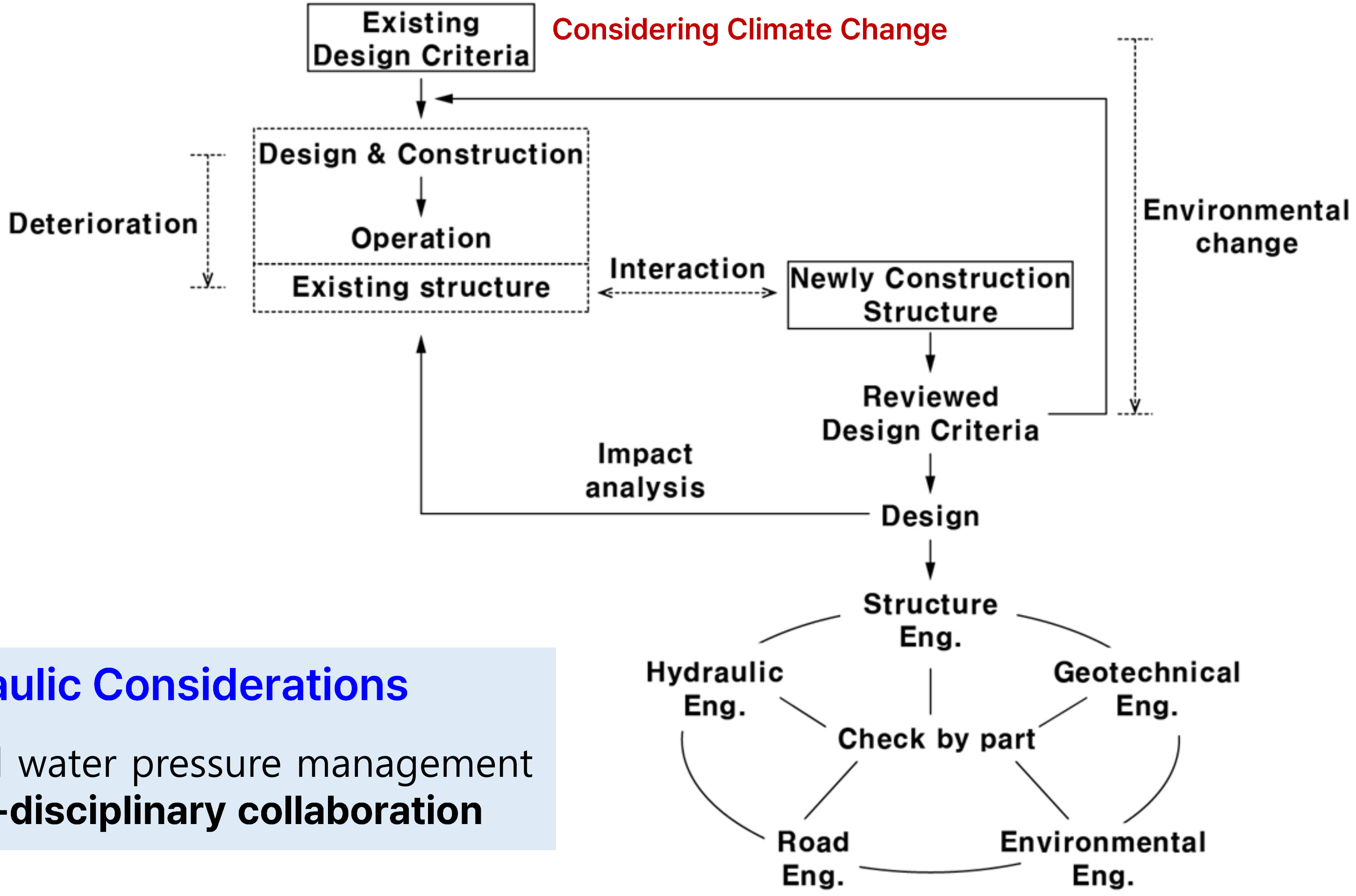
  - Drainage system **(Q control)**
  - Grouting **(Q,P control)**
  - Structural measures **(P control)**

  ➡ **Micro scale, Structural Measures**

Integrated Control System

Hydrological Considerations

Flooding and pressurization management due to surface water



Existing Design Criteria

Considering Climate Change

Deterioration

Design & Construction

Operation

Existing structure

Interaction

Newly Construction Structure

Environmental change

Reviewed Design Criteria

Impact analysis

Design

Structure Eng.

Hydraulic Eng.

Geotechnical Eng.

Check by part

Road Eng.

Environmental Eng.

Hydraulic Considerations

Drainage and water pressure management and **cross-disciplinary collaboration**

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