Maintenance of Tunnels

July 7th 2016 Lecture at Waseda Univ.

Shinji KONISHI

Contents

1 Case studies on tunnel deformation

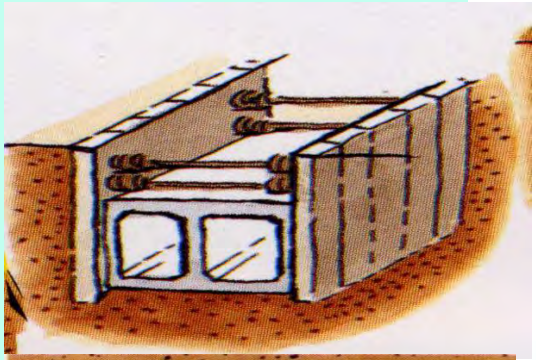
Types of Tunnel & Construction Methods

What's Tunnel?

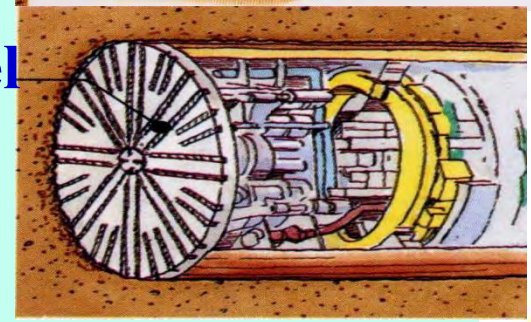
What's a tunnel made of ?

Types of Tunnel

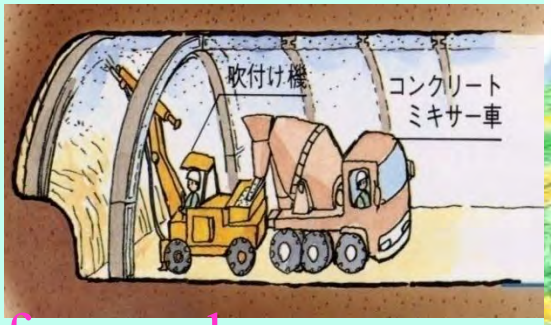
Cut & Cover Tunnel



Shield Tunnel



Mountain Tunnel

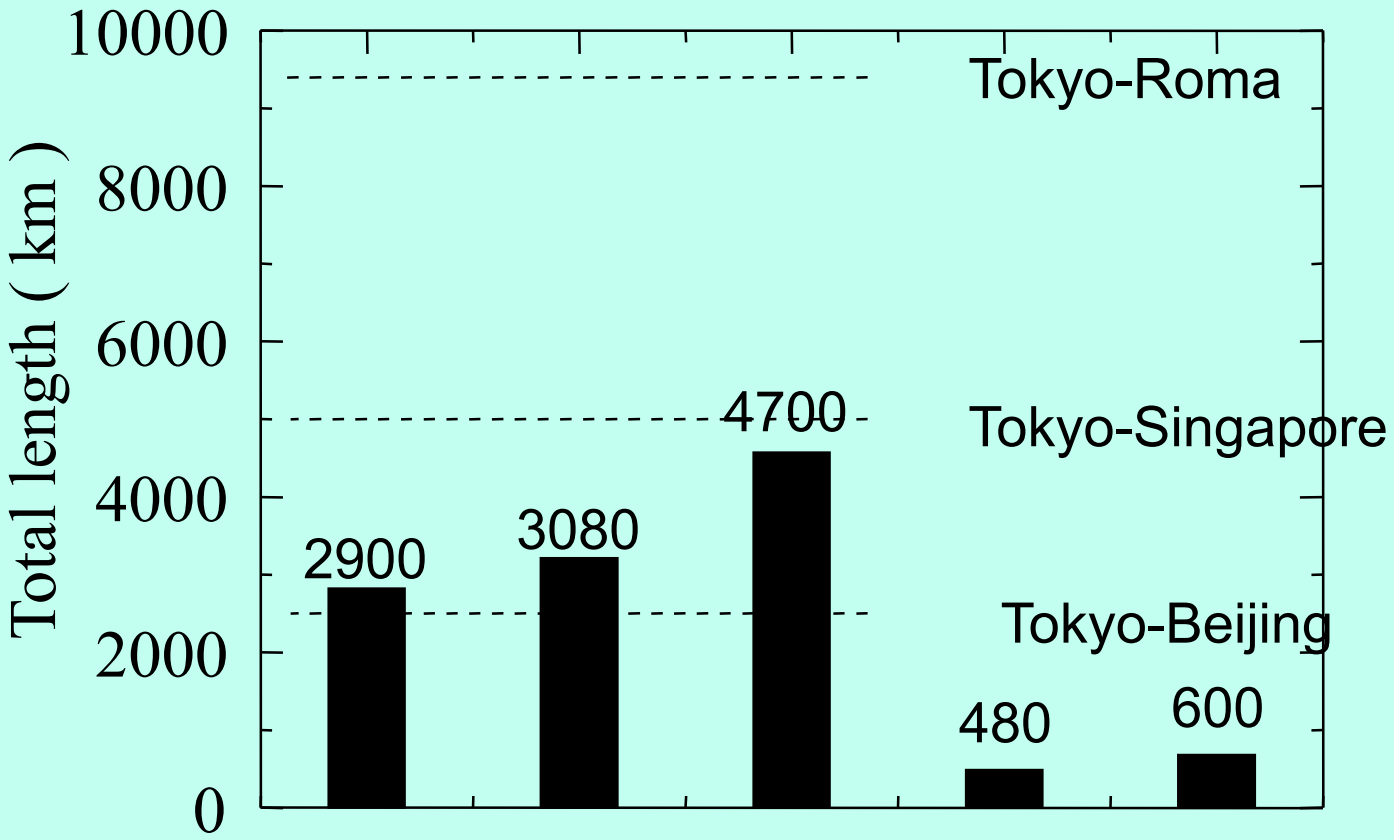


Difference of ground

Difference of construction method

Total length of tunnels in Japan

トンネルと地下(2006.4)



Data from

道路統計年報（2004）	鉄道総研 (2002）	発電用導水路 (沖縄電力を除く)	東京電力洞道	NTT洞道

Total quantity of Tunnels in Japan

Railway tunnel	**About 4800 tunnels, 3,300km (at 2002)**
Road tunnel	**About 8500 tunnels, 2,700km (at 2001)**
Headrace tunnel for power generation	**About 4,700km (at 1997)**
Sewage tunnels of Tokyo	**About 15,000km**
Railway shield tunnel	**About 250km (at 2002)**

Shimizuyato tunnel

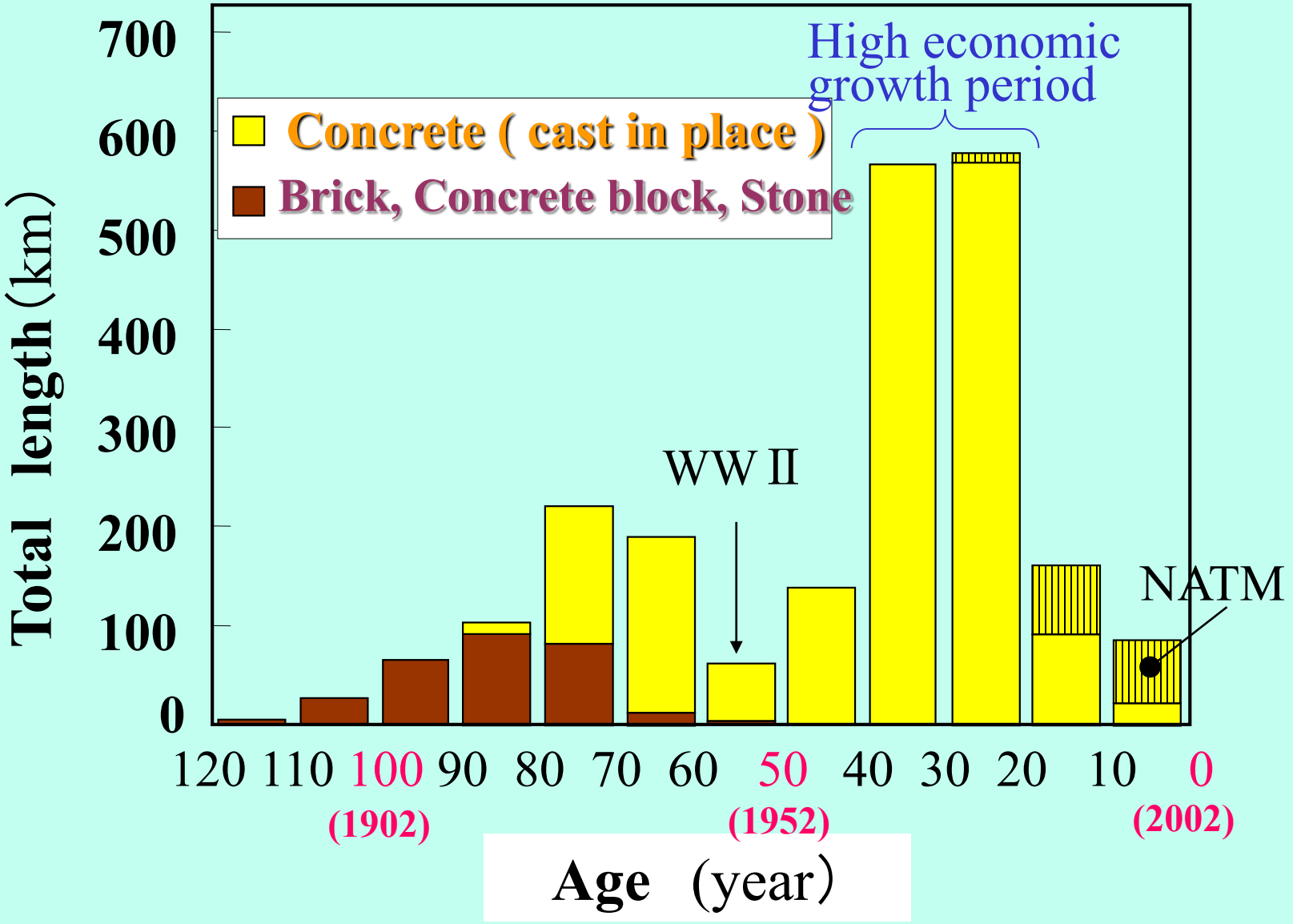
Between Yokohama and Higashitozuka in JR Tokaidou line

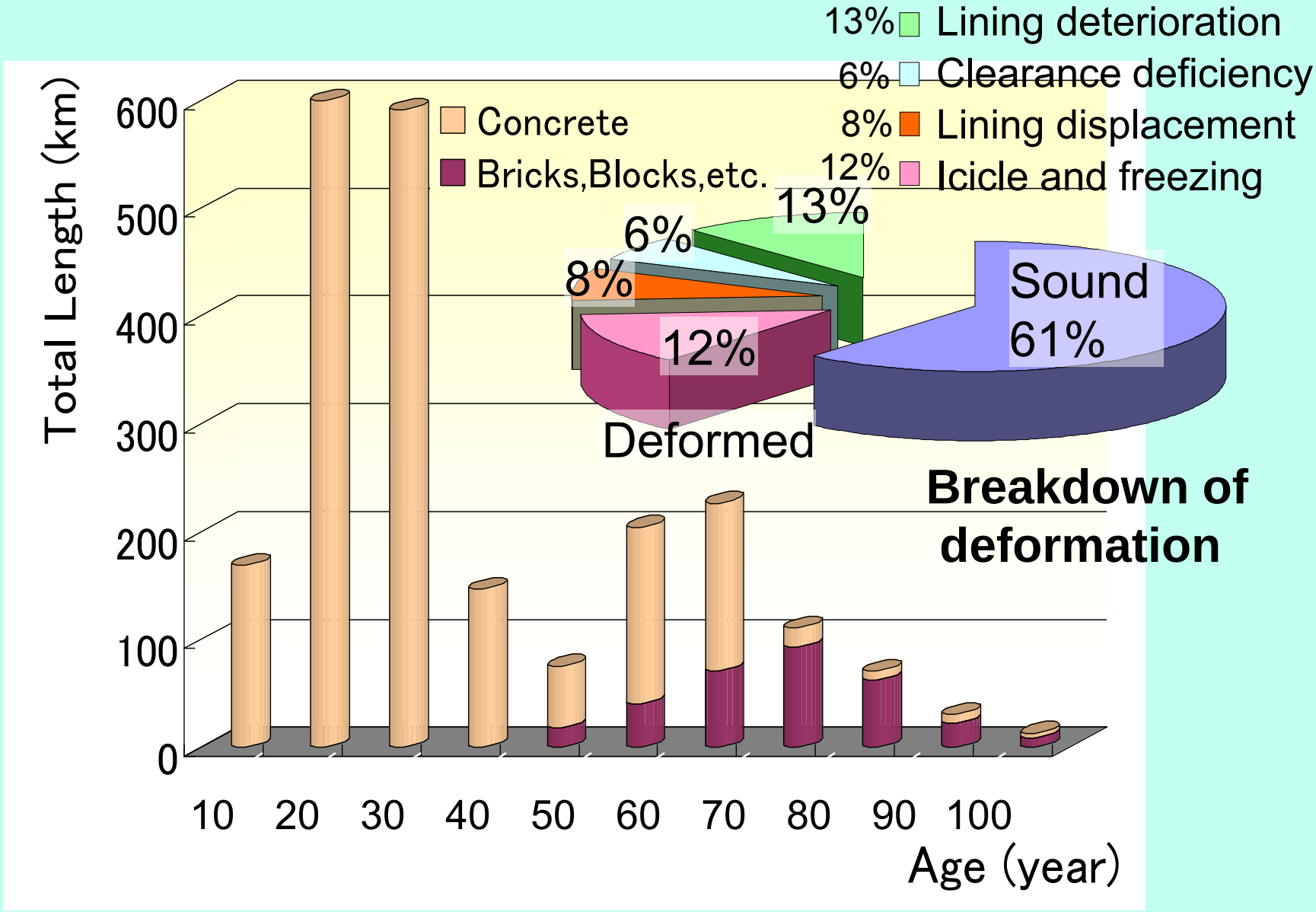
127 years old

⇒ *Tunnels are very long life structures.*

Age distribution of railway tunnels in Japan

(since 2002, by RTRI)





Railway tunnel age in Japan

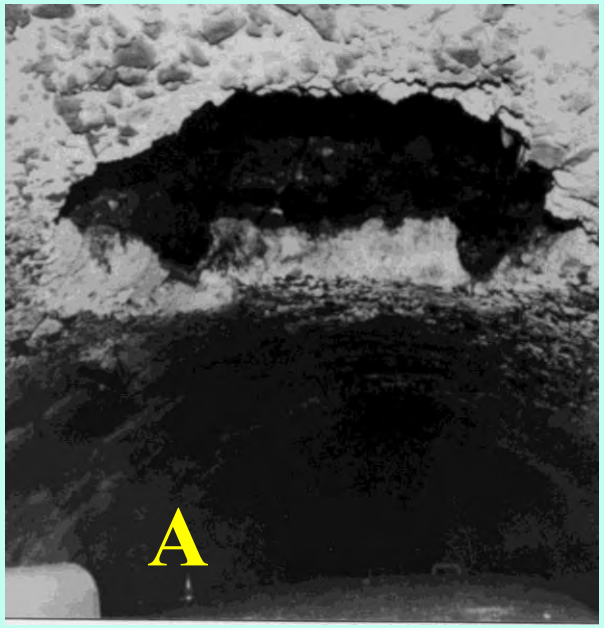
1 Case studies on tunnel deformation

The State of Mountain Tunnels

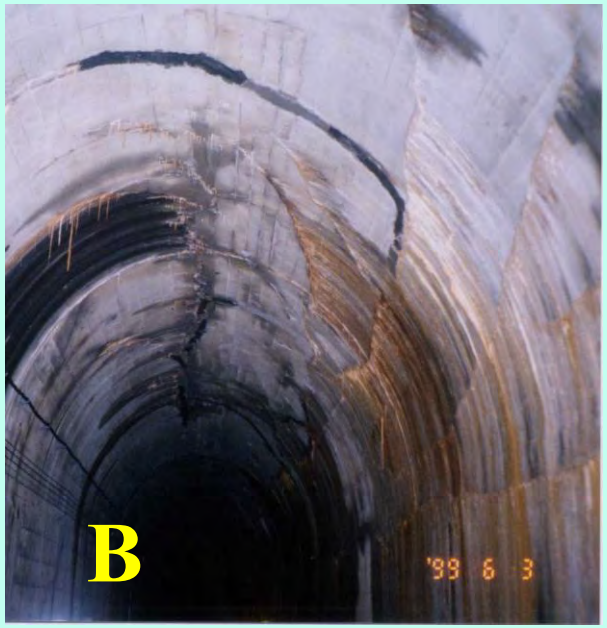
Examples of deformation

What's happen ?

Why do those deformations happen ?



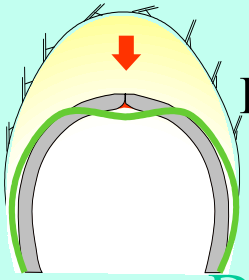
Punching failure



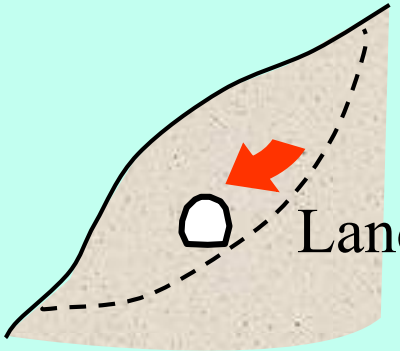
A number of cracks

Compressive failure

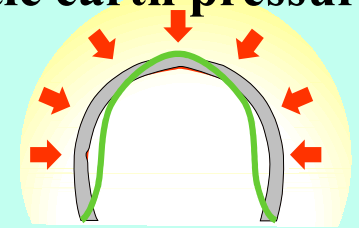
Examples of deformation caused by earth pressure



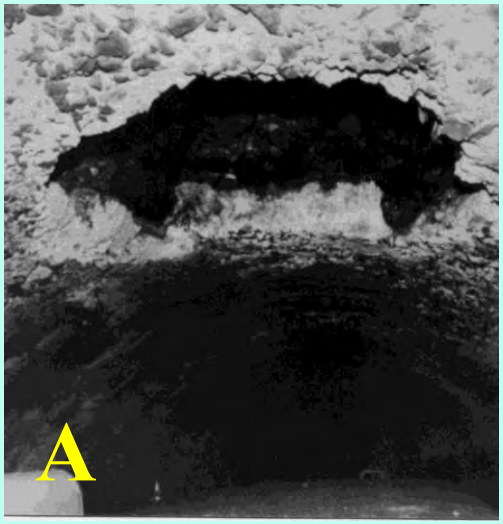
Loosening



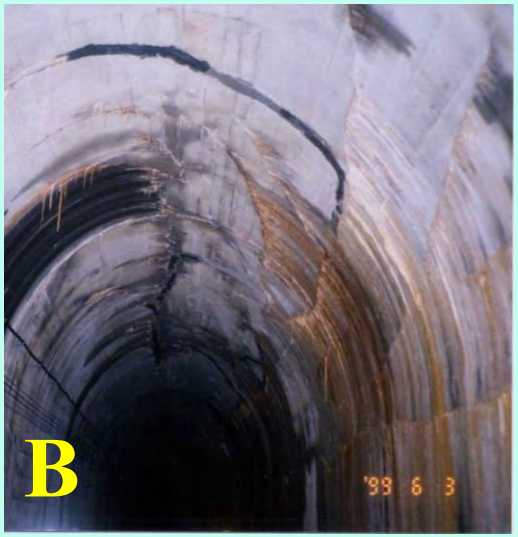
Plastic earth pressure



Deformation

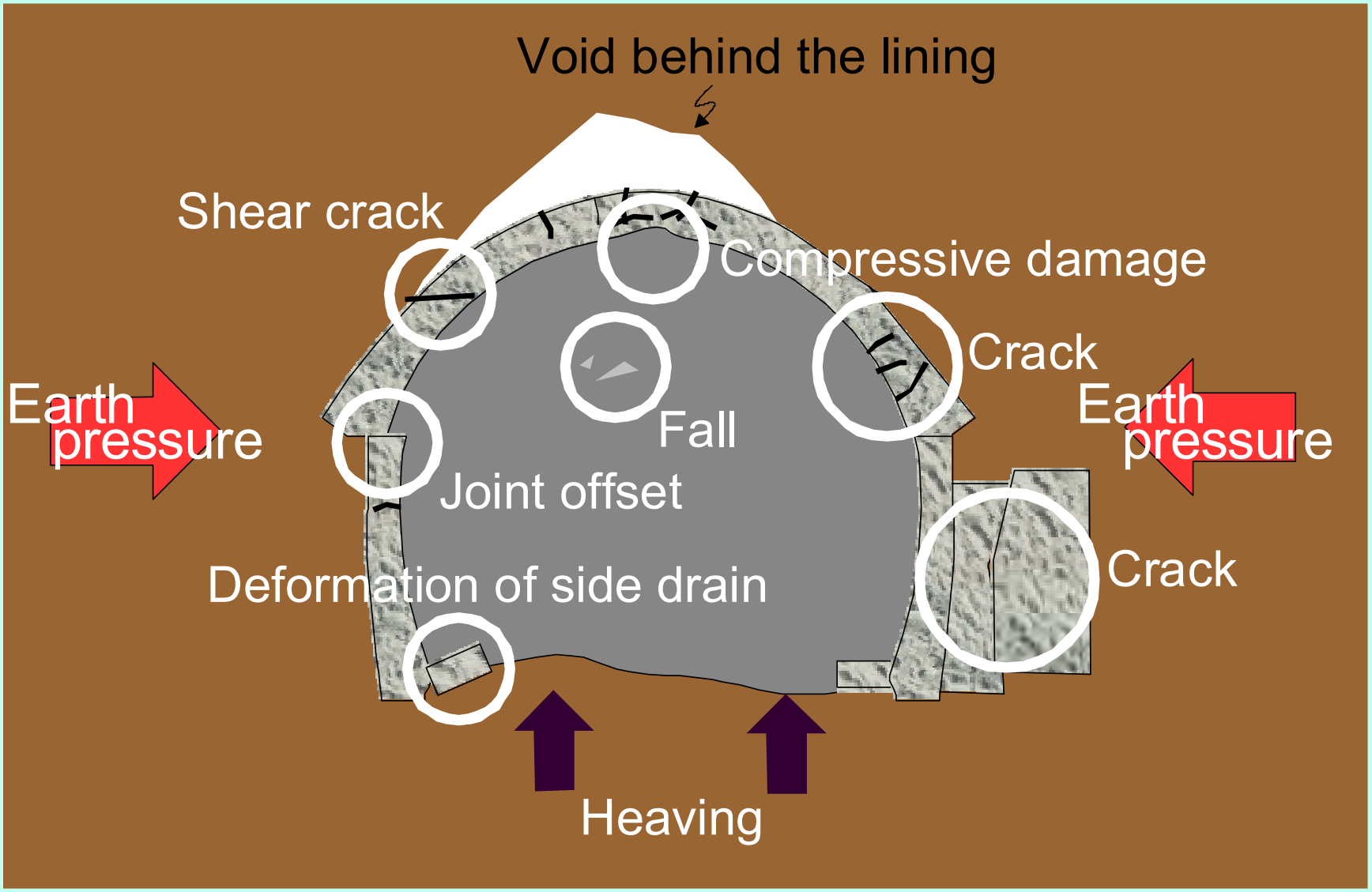


Punching failure
caused by
vertical pressure
due to ground loosening



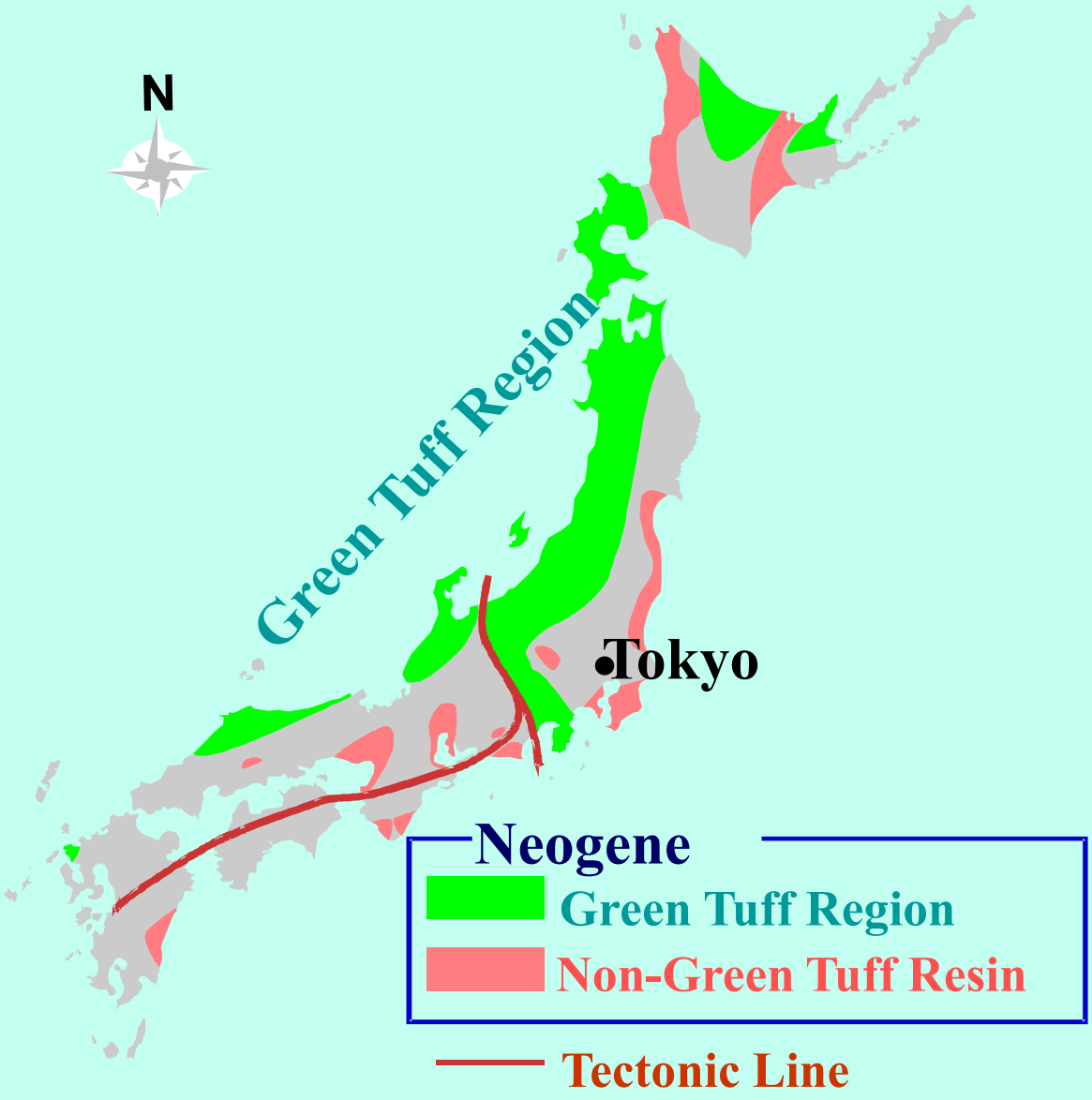
A number of cracks
caused by
landslide

Compressive failure
caused by
plastic earth pressure

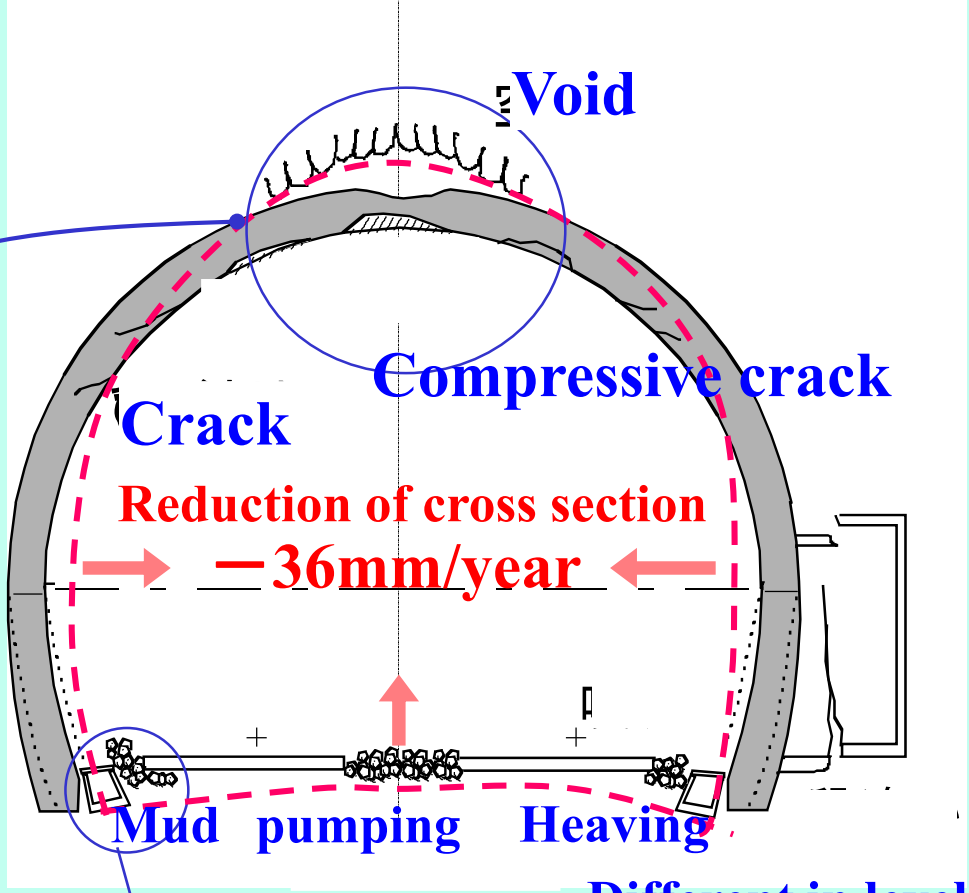


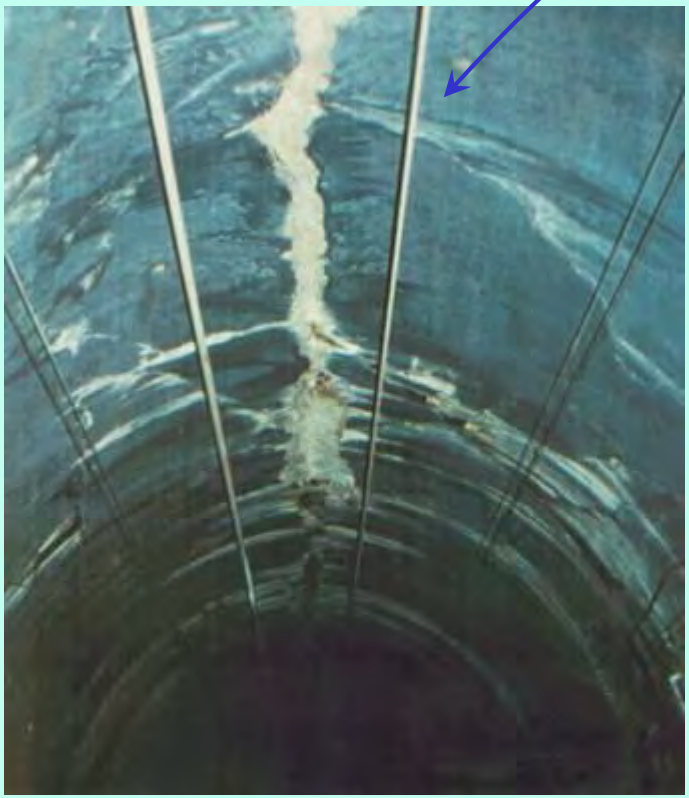
Example of deformation by earth pressure

Distribution of Neogene rocks in Japan



Primary deformation





Compressive crack of crown
=>spolling

Different in level

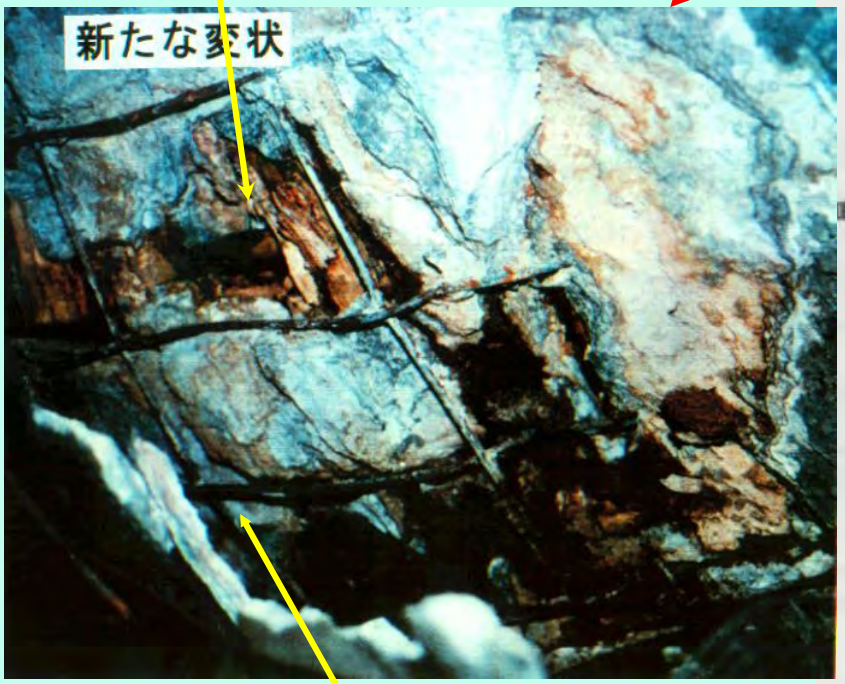
Damage of side drain

=>Poor drainage,
stagnant water

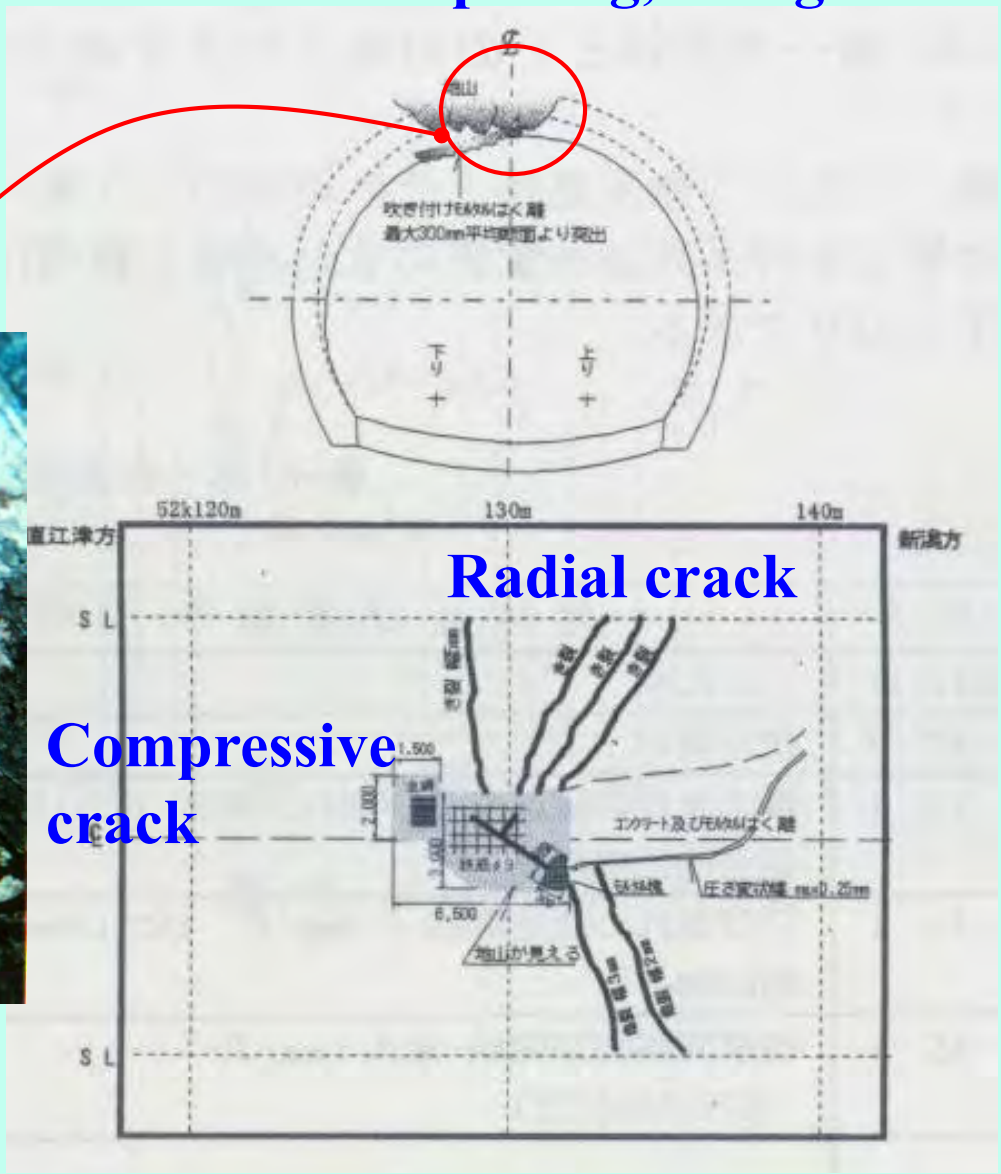
Secondary deformation

Spolling, Hung down

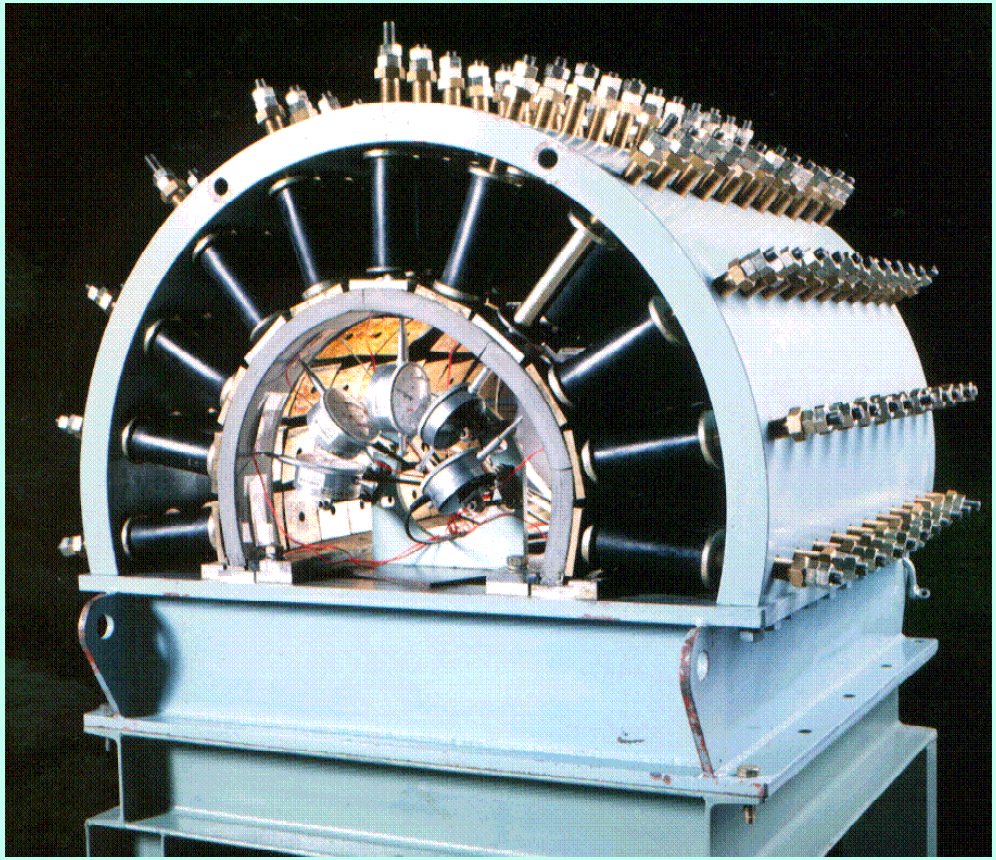
Ground



Spolling, Hung down



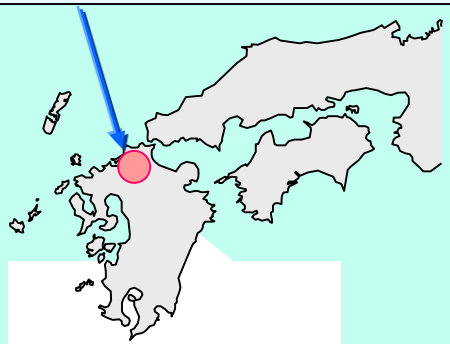
Development view

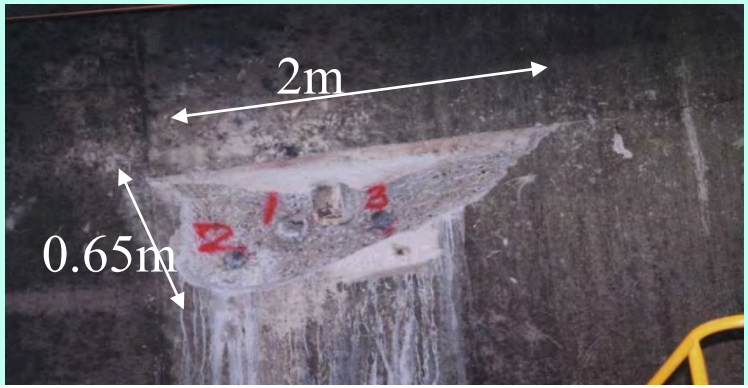


Tunnel lining test unit

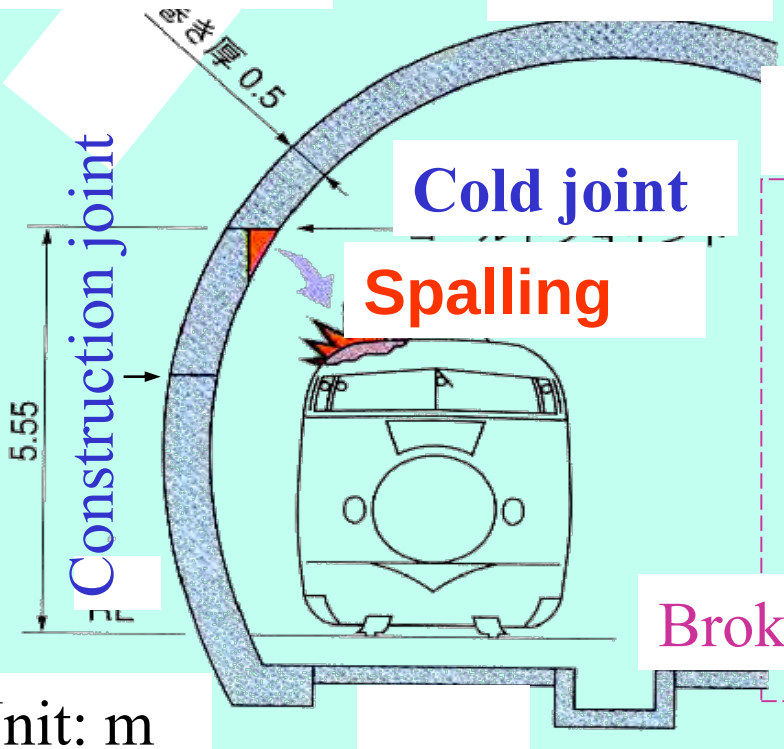
Accident occurred by spalling of tunnel lining concrete

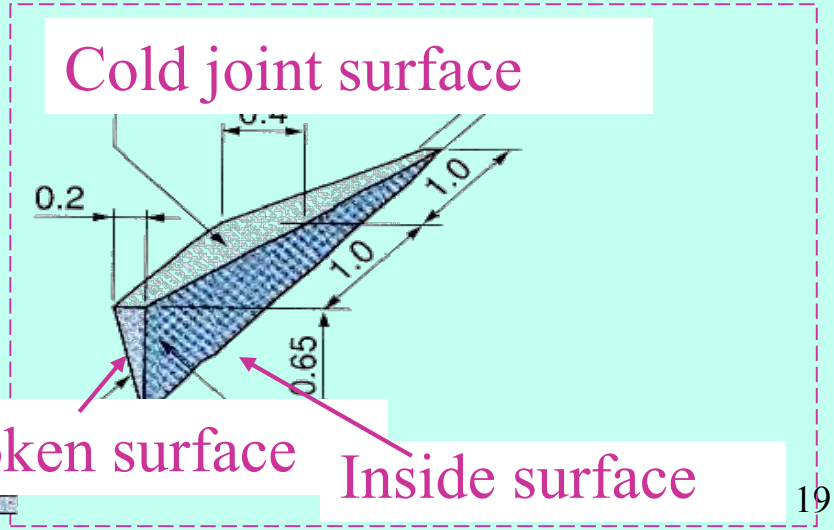
Fukuoka Tunnel (Sanyo Shinkansen line), 1999





Spalling concrete block

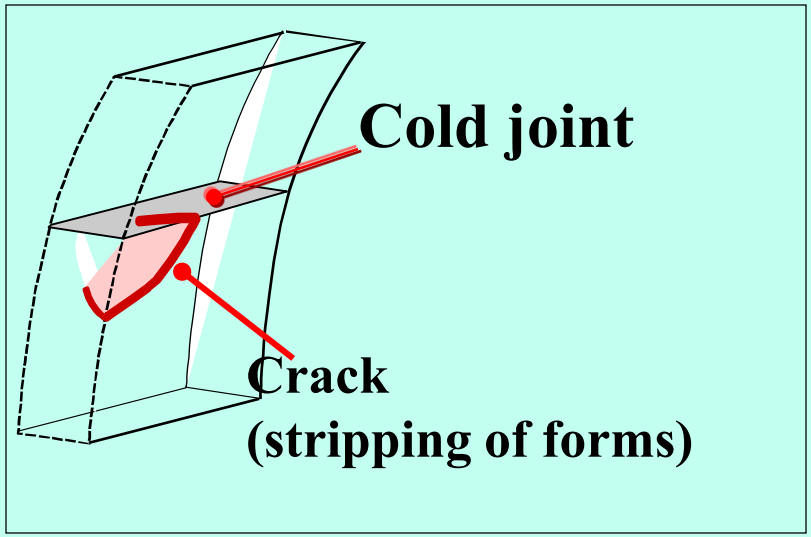




Unit: m

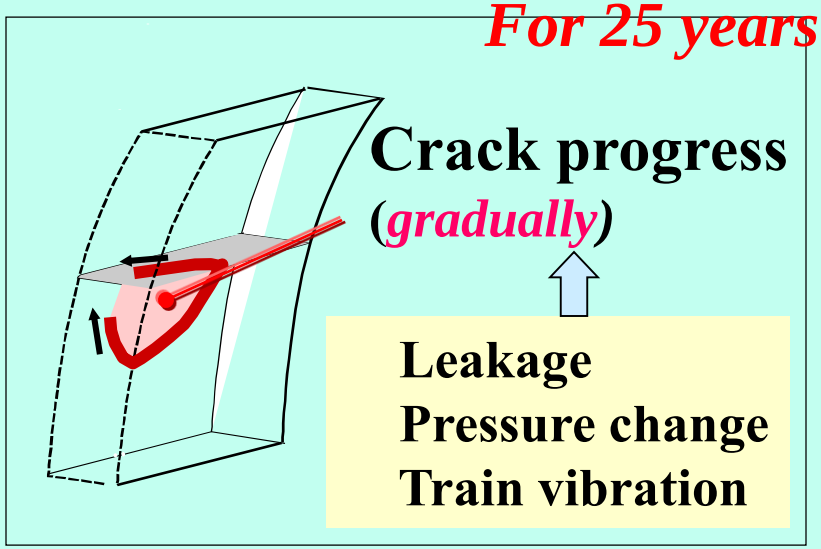
Spalling mechanism (As a result of examinations)

(1) During Construction



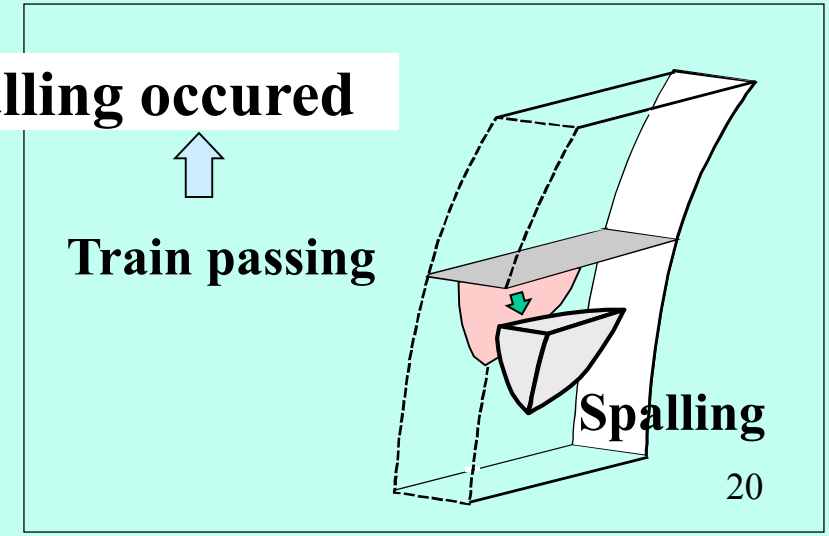
(2) After being in operation

For 25 years



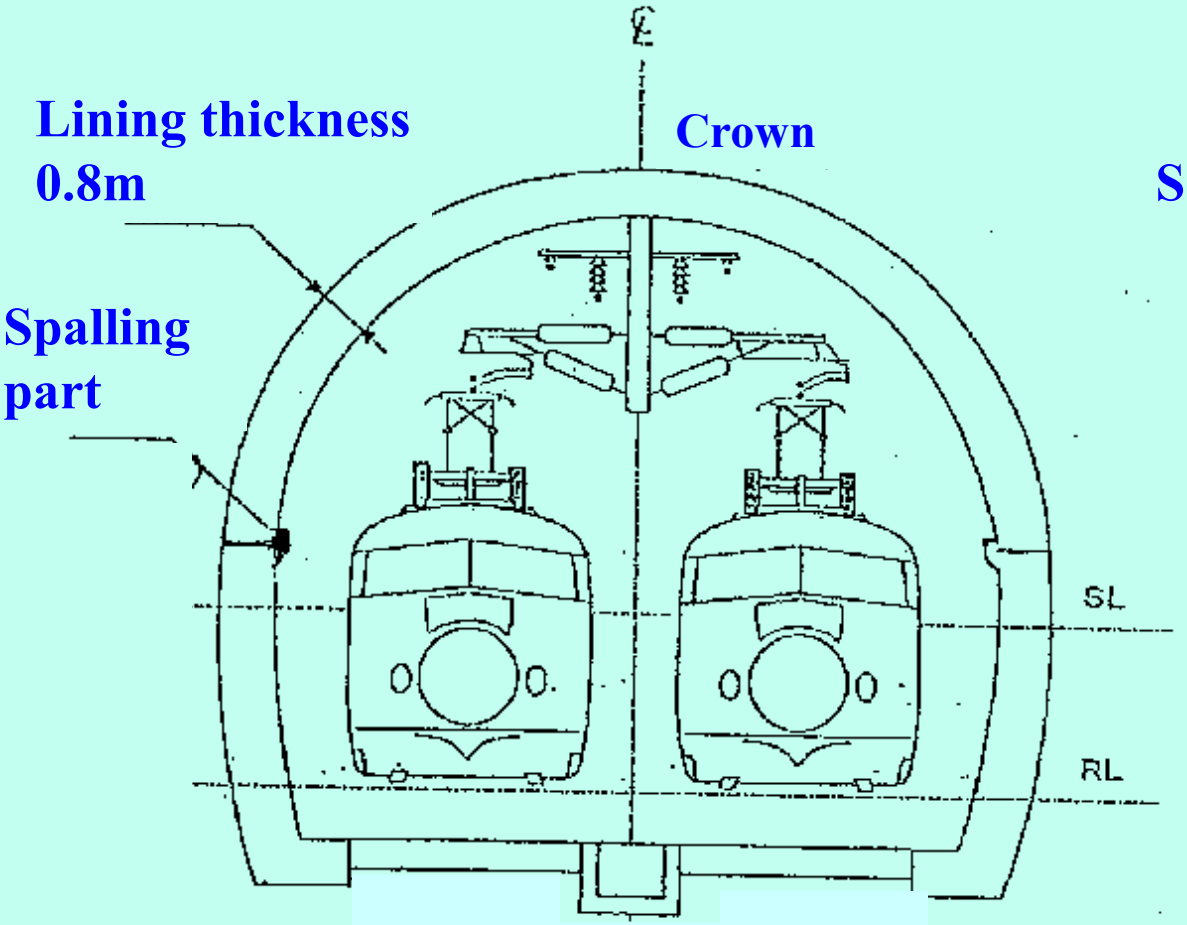
Attention was not paid to the cracks
(not enough inspected)

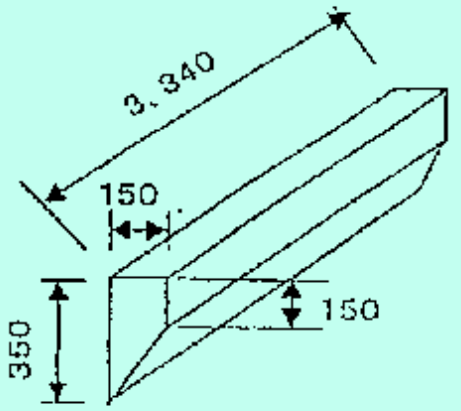
(3)Spalling occured



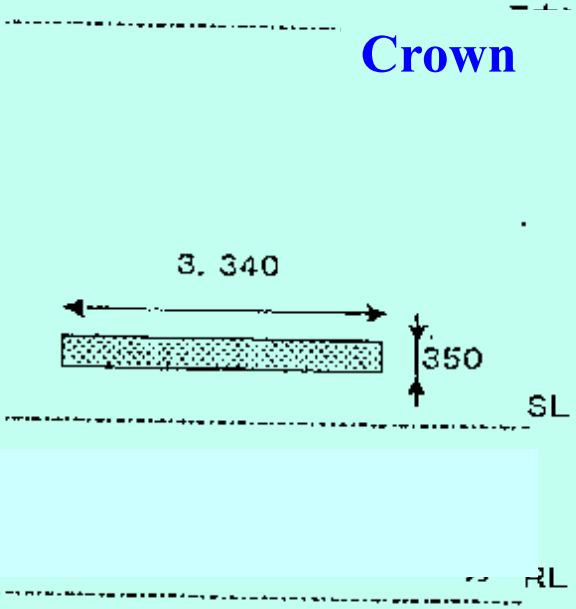
- B tunnel

Outline of spalling part



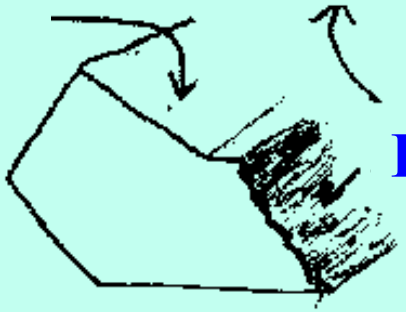


Shape of spalling part



Lining of B tunnel after spalling

Spalling surface



Breaking surface

External factors

- Earth pressure and water pressure
- Adjacent construction
- Train vibration
- Air pressure change

etc

Internal factors

- Cast in chloride t
- Improper construction
  - -compaction
  - -placing
  - -early removing of form
  - -Form oil
  - -Settlement of side wall leg
  - -Settlement of form

  etc

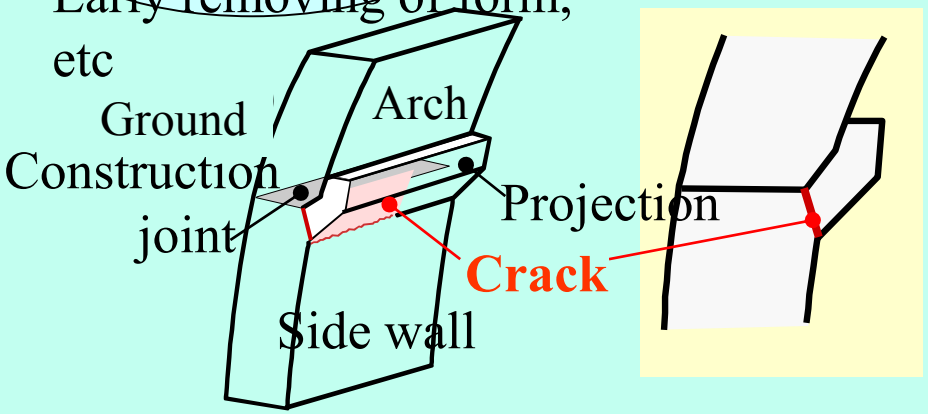
?

Assumed main factors of the accident

①

Settlement of concrete, side wall, form
Early removing of form, etc

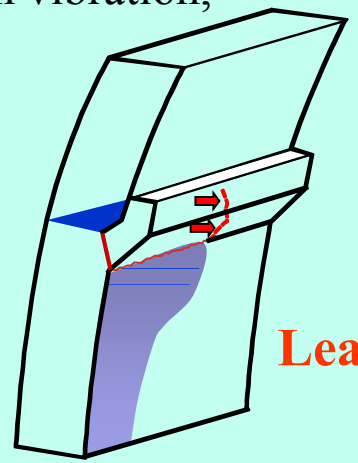
Generation of crack



②

Leakage,
Changes of temperature,
Train vibration,
etc

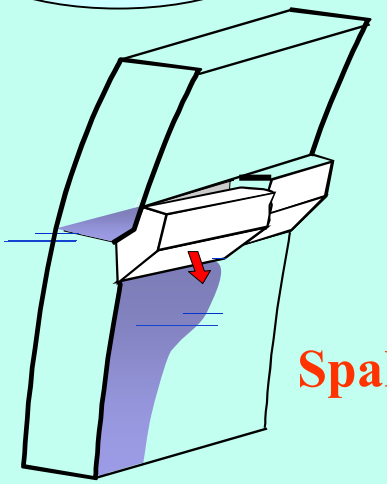
Growth of crack



③

Self-weight

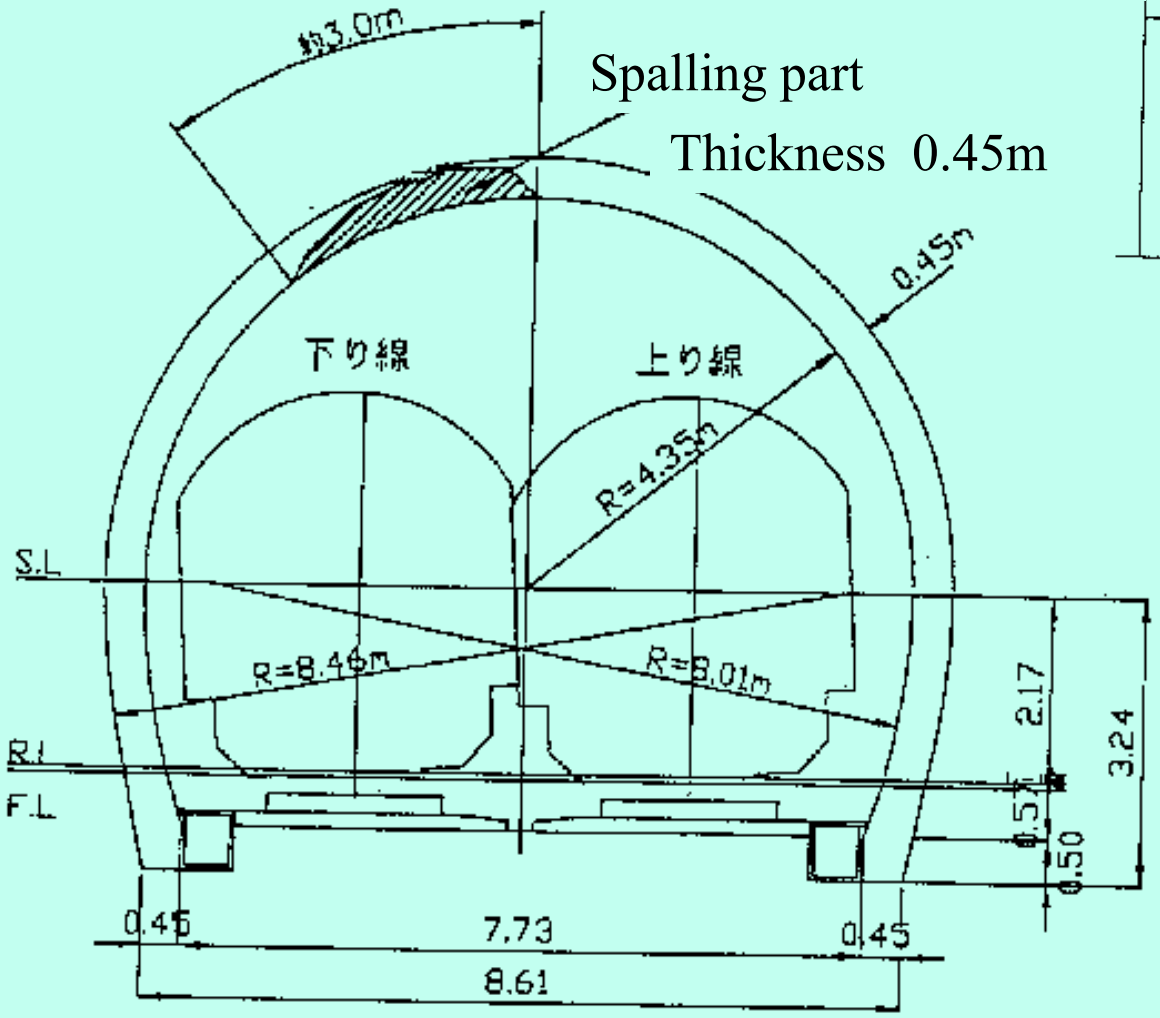
Spalling



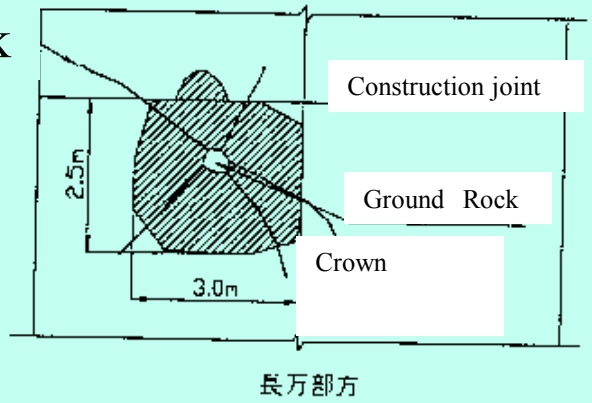
Assumed mechanism of spalling in B tunnel

C tunnel

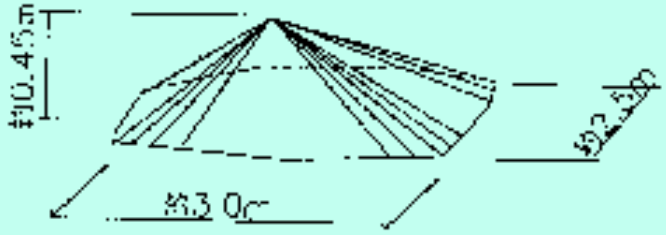
Outline of spalling part



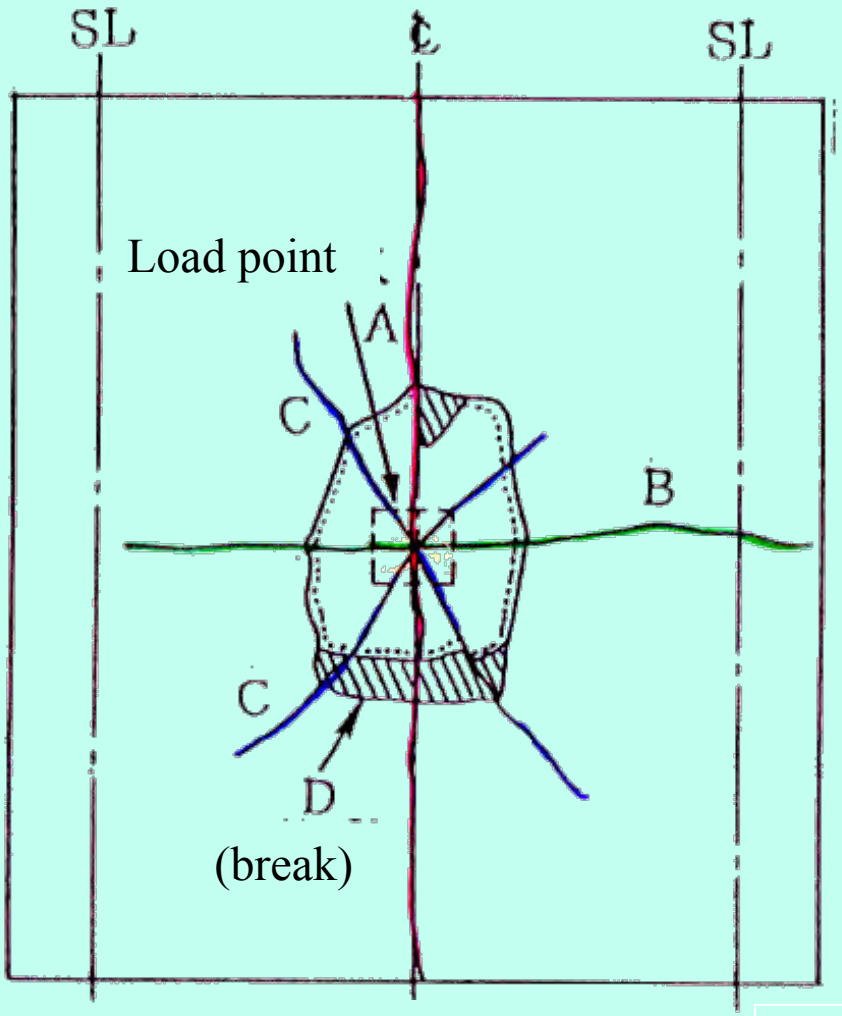
Higashimuroran side



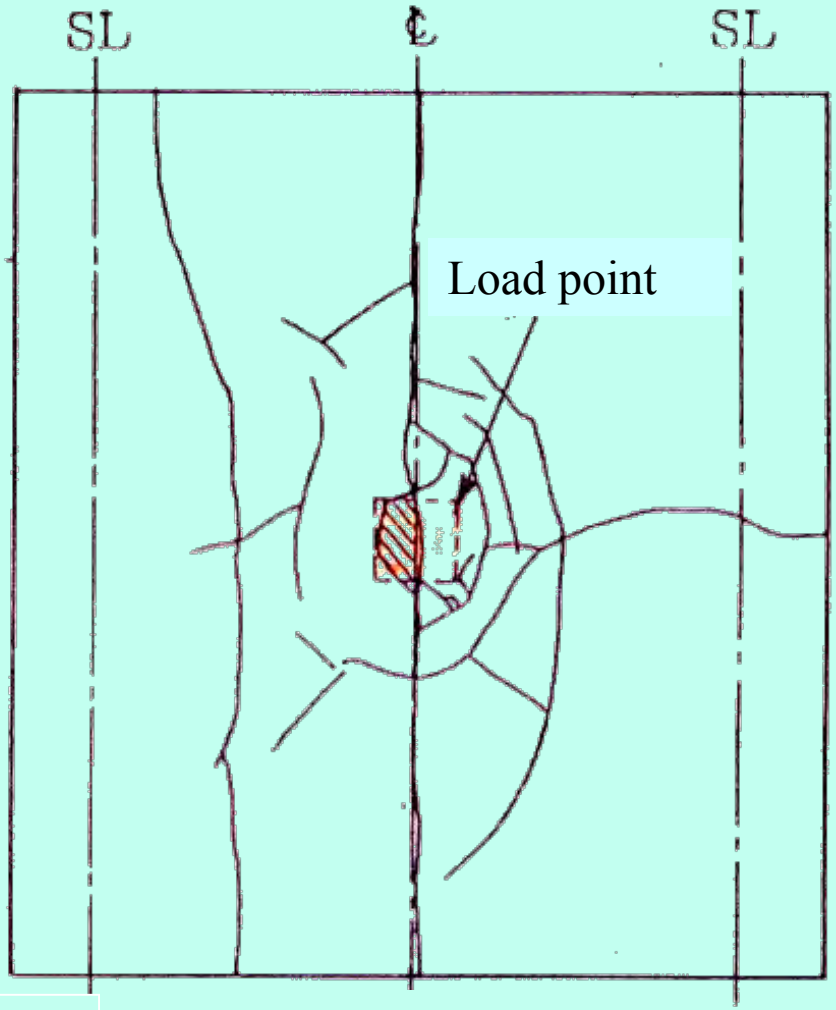
Oshamannbe side



Lining of C tunnel after spalling



Inside



Outside

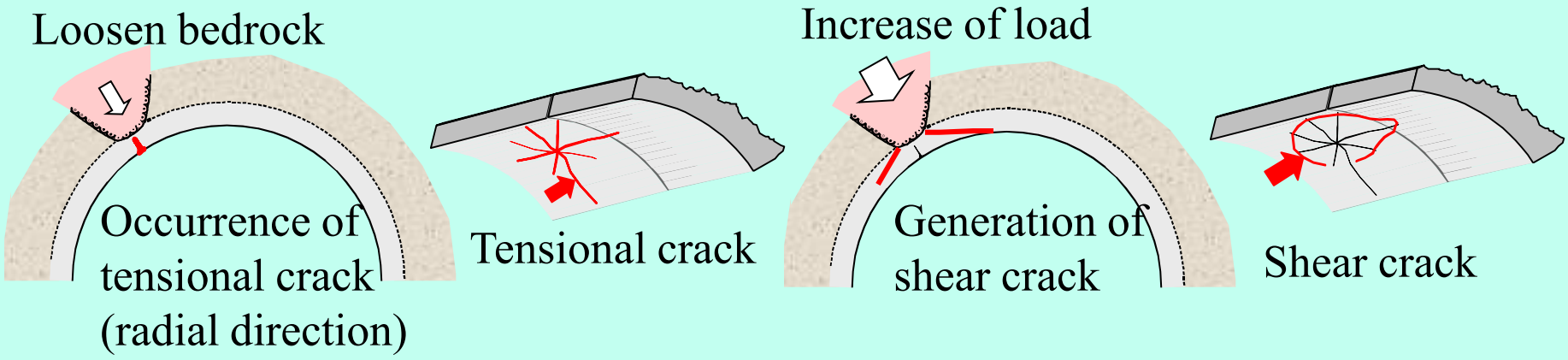
Shear crack

Radial cracks

Tensional crack

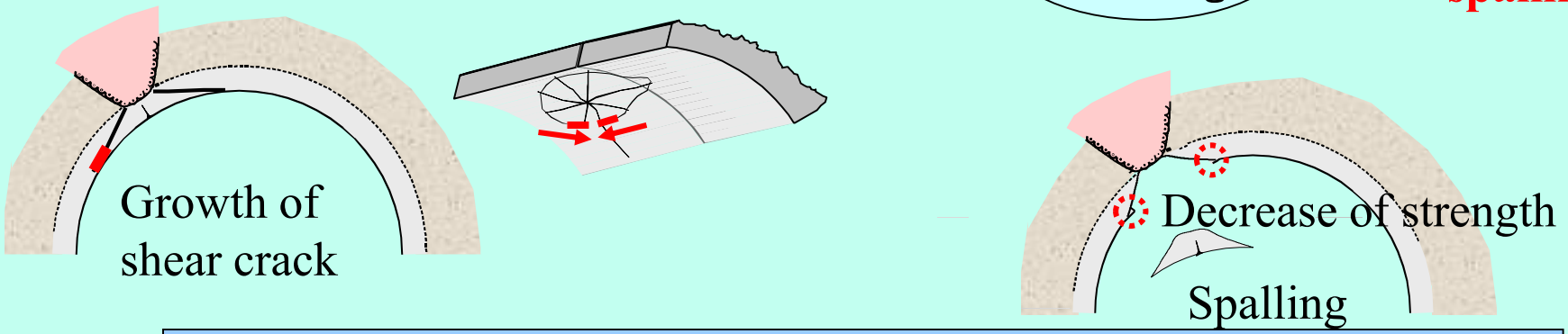
1 Loosen bedrock due to placing → Generation of tensional crack (radial direction)

2 Increase of load → Generation of shear crack



3 Train vibration, Freezing → Growth of shear crack

4 Decrease of strength → **Break・spalling**



Assumed mechanism of spalling in C tunnel

Precepts of accidents

1. Crack generated at initial stage.

=♦Sure inspection.
(Observation,Hammer tapping)

♦Initial comprehensive inspection.

2. A blind spot in inspection.
(Cold joint,Projection)

=♦Reconsideration of check points.

♦Perfection of reference book.

Seismic hazard of Railway Tunnel

Chuetsu earthquake(**M6.8**) (2004)

Jyoetsu Shinkansen Uonuma T. ⇒ Restoration work for 2 months

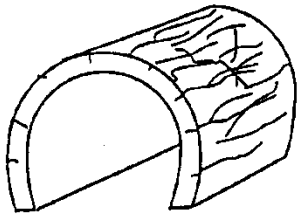
⇒Countermeasure of tunnels for large earthquake is important.

Cracks due to conditions of environment or using

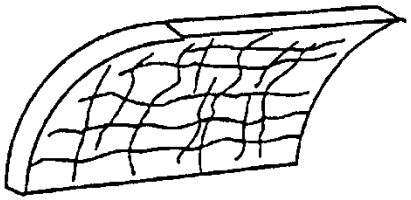
使用･環境条件によるひび割れ

2-1 地圧以外によるひび割れ

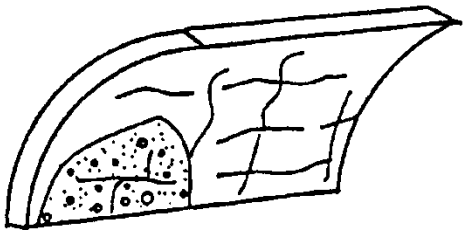
使用・環境条件に関係するもの



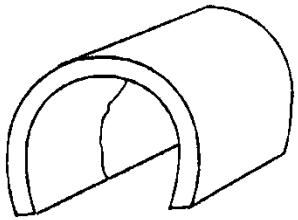
1 凍結融解の繰返し
隅角部や水平ジョイント部の斜めひび割れや長手方向のひび割れ、スケーリングなどが特徴である。



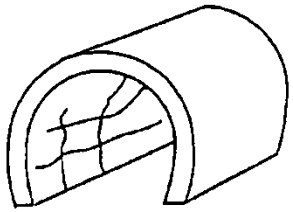
2 火災、表面加熱
急激な温度上昇と乾燥とにより網目状の微細なひび割れとともに梁、柱にほぼ等間隔の太目のひび割れが入る。また、部分的に爆裂して剥落することがある。



3 酸・塩類の化学作用
コンクリート表面が侵され、多くは鉄筋位置にひび割れが生じ、一部コンクリート表面が剥落することもある。露出した鉄筋の進行は激しい。



4 部材両面の温度・湿度の差
外部が高温または高湿、内部が低温または乾燥の場合、ひび割れは拘束部材隣接部付近の低温または乾燥側に発生する。初期の段階では、ひび割れは貫通していないが、繰返し作用により時間がたつと貫通することがある。



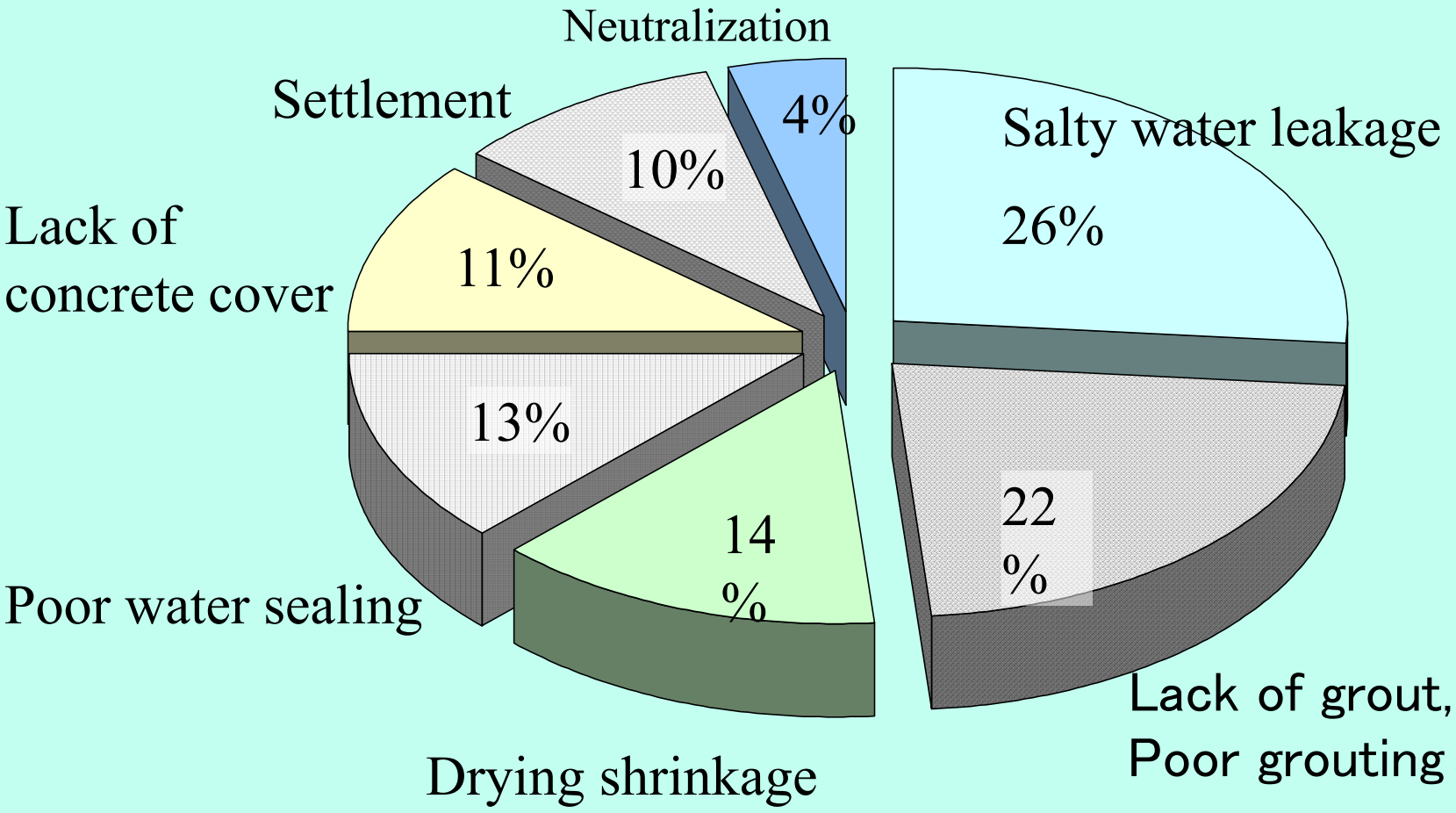
5 中性化による内部鉄筋の錆、侵入塩化物による内部鉄筋の錆
ひびわれは、鉄筋に沿って発生する。ひび割れ部分からは錆が流出し、コンクリート表面を汚すことが多い。鉄筋の腐食が著しい時にはコンクリートの剥落もある。

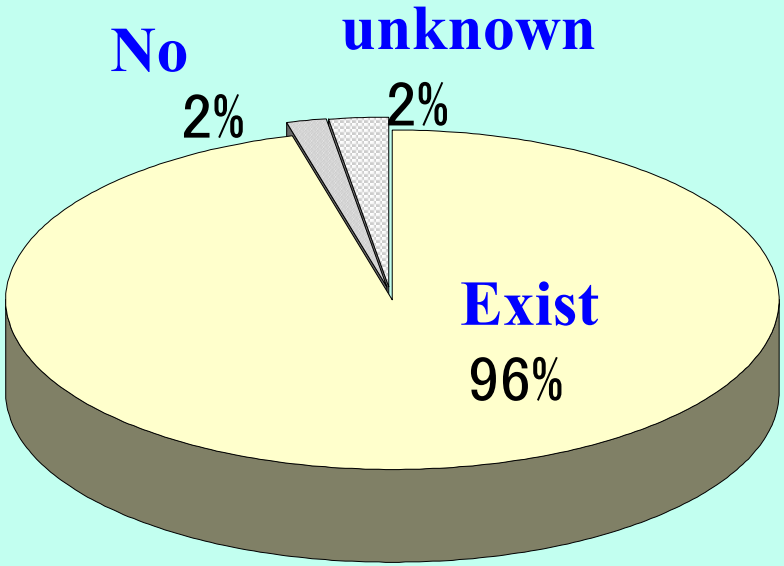
1 Case studies on tunnel deformation

The State of Shield Tunnels

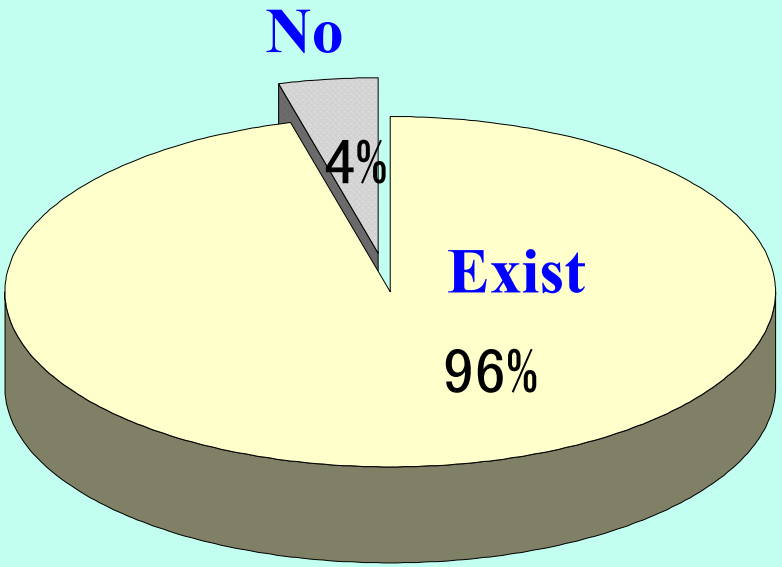
Shield tunnel

Rate of shield tunnels suffering from deterioration

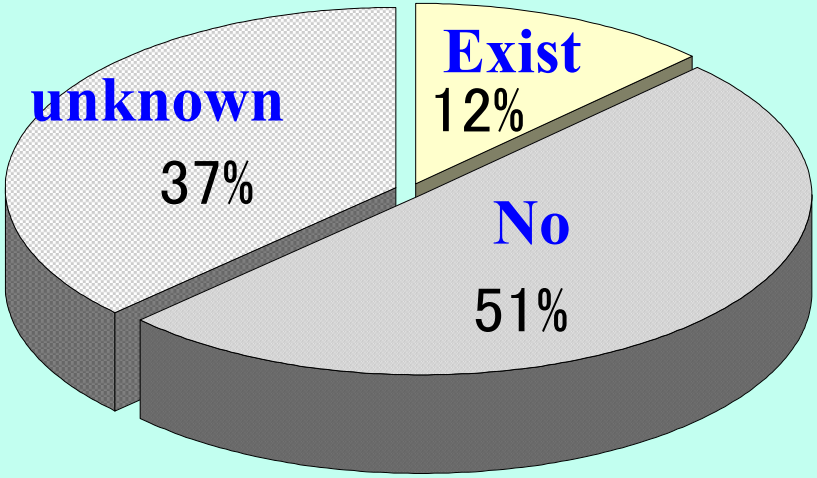




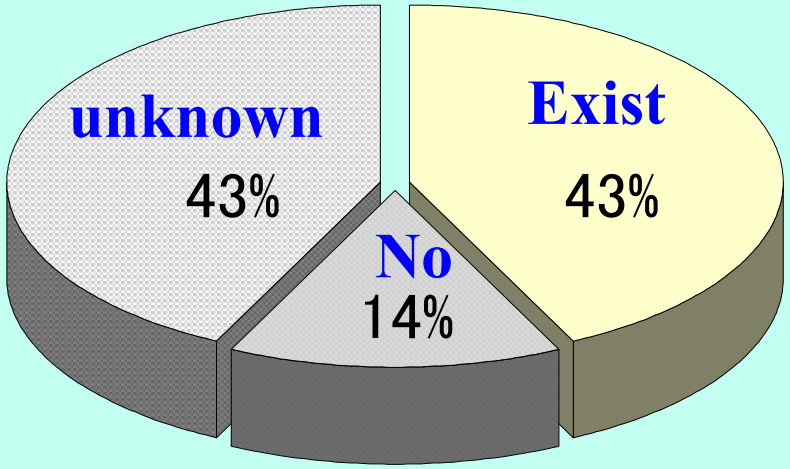
Crack



Leakage of water



Degradation of concrete



Corrosion of iron joint

Shield tunnel

Newly-made Shield tunnel

Degradation of segment and joint

Aperture of a joint

Chips

Leakage of Secondary Lining

Leakage from Joints of Segmental Lining

Adhesion of Dust due to Leakage

Corrosion of Rail Track due to Leakage

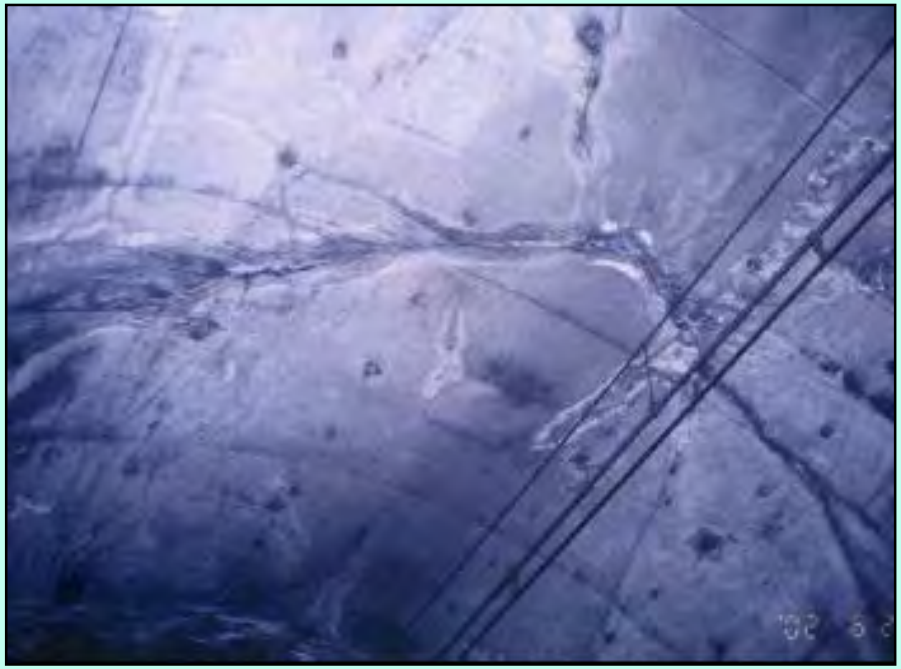
Iron Bacteria

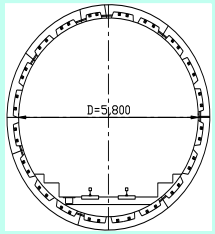
Corrosion of bolts

Explosion of a Joint Bolt

Longitudinal Crack of a Secondary Lining due to Settlement

Cracks of Secondary Lining due to Behind Restraining Stress





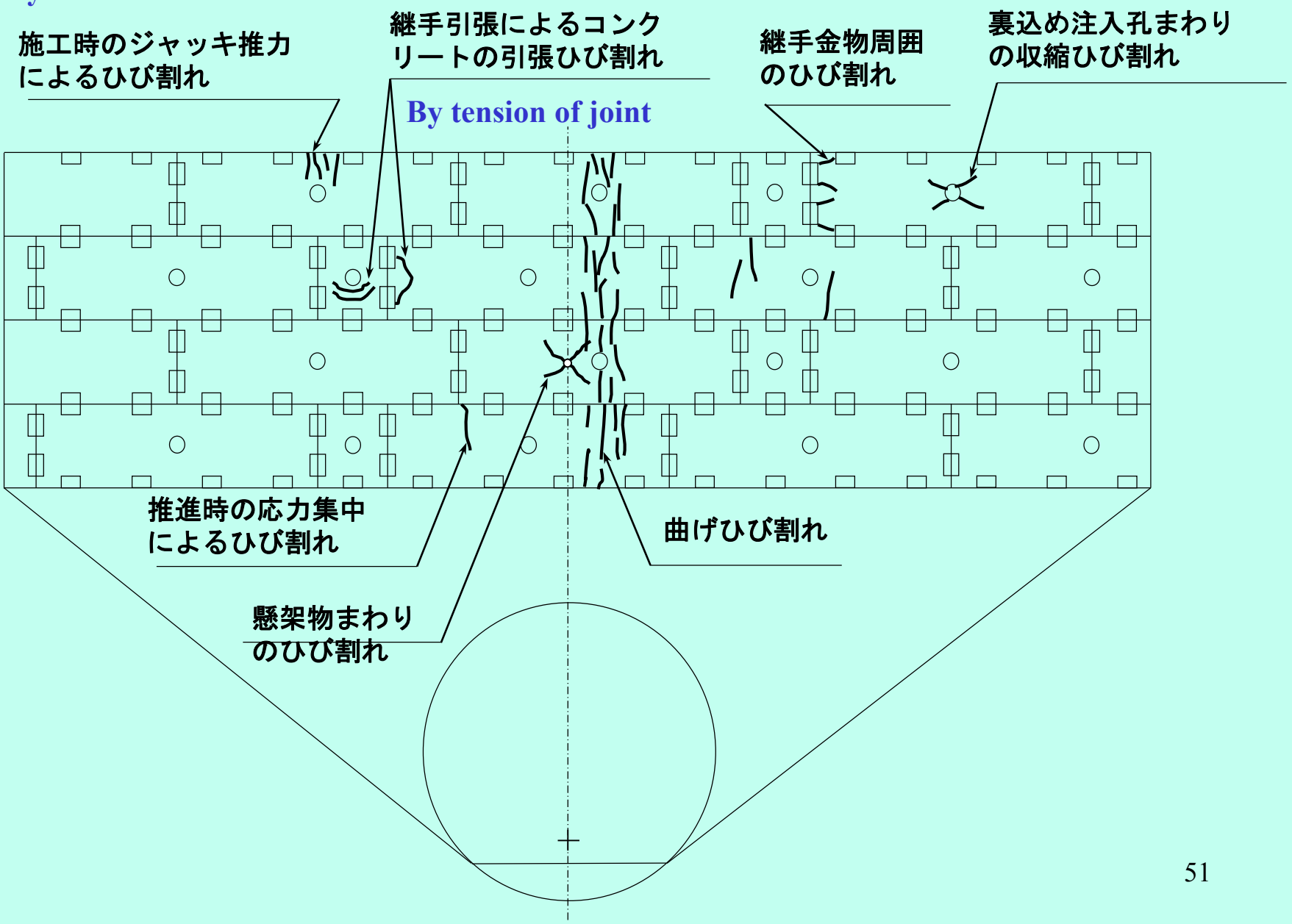
Shield tunnels

- Leakage from joints
- Bolts beginning to rust
- Rebar corrosion

Deformation (Salt Damage-2)

Exposure of Reinforcing Bar due to Lack of Cover Concrete

Cracks of shield tunnels



1 Case studies on tunnel deformation

The State of Cut & Cover Tunnels

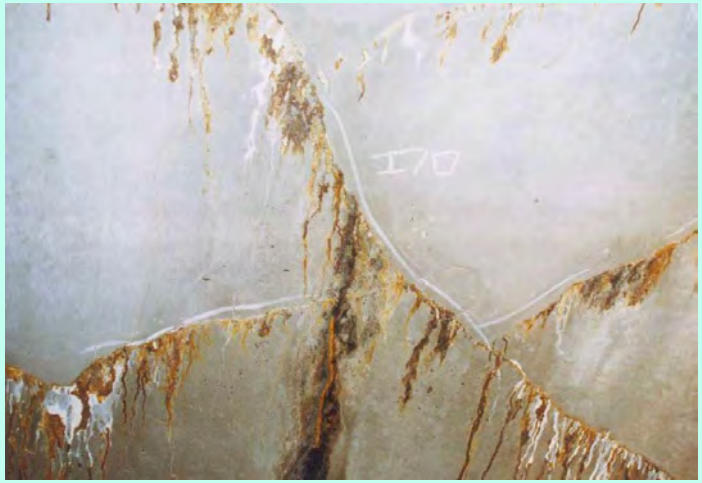
Flaking of cover concrete

Defection of concrete section

Exposure and corrosion of reinforcing bar

Crack

Efflorescence

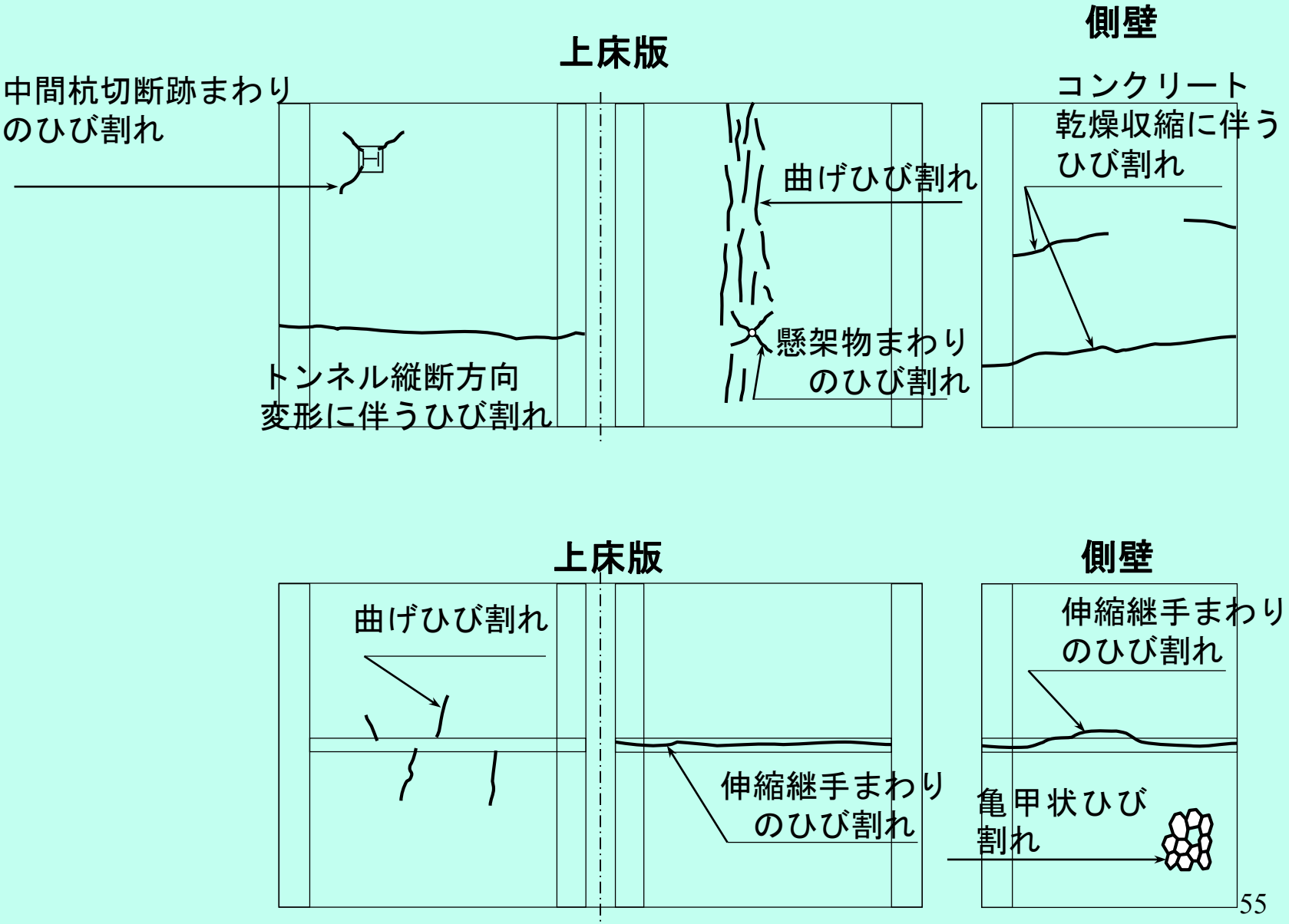


Free lime

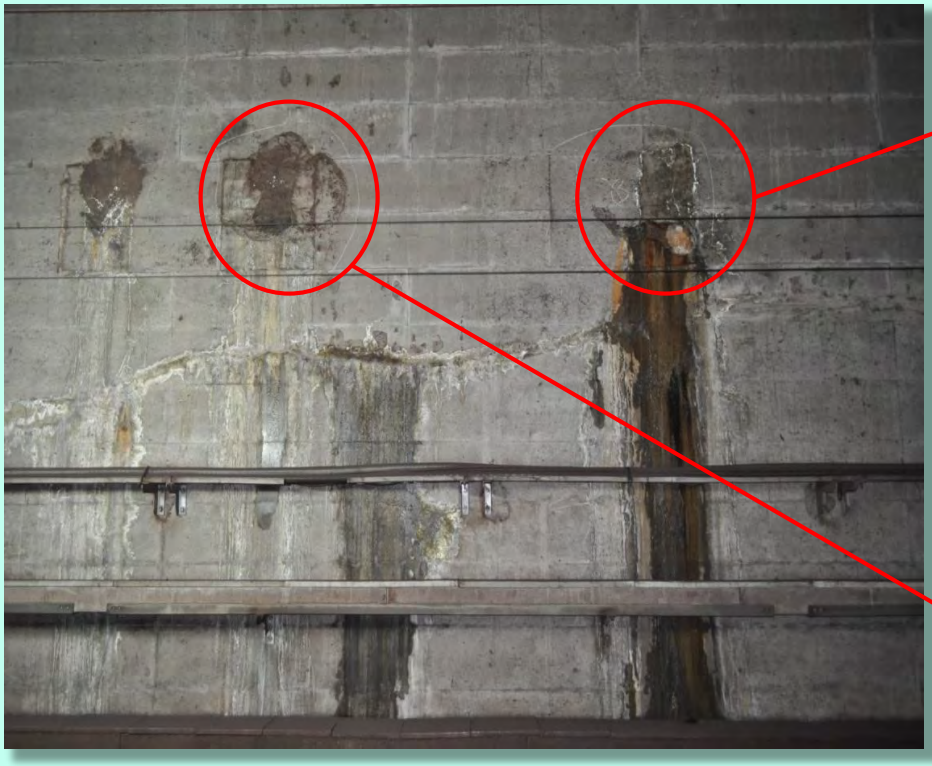
Water leakage

Segregation (Rock pocket etc.)

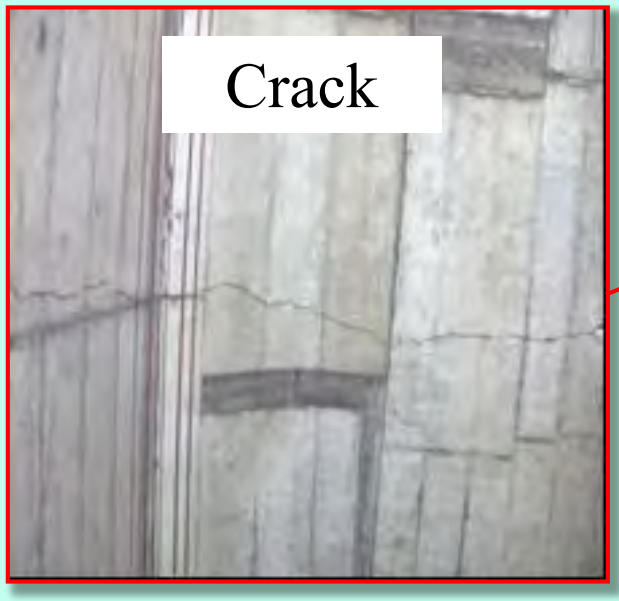
Cracks of cut & cover tunnels

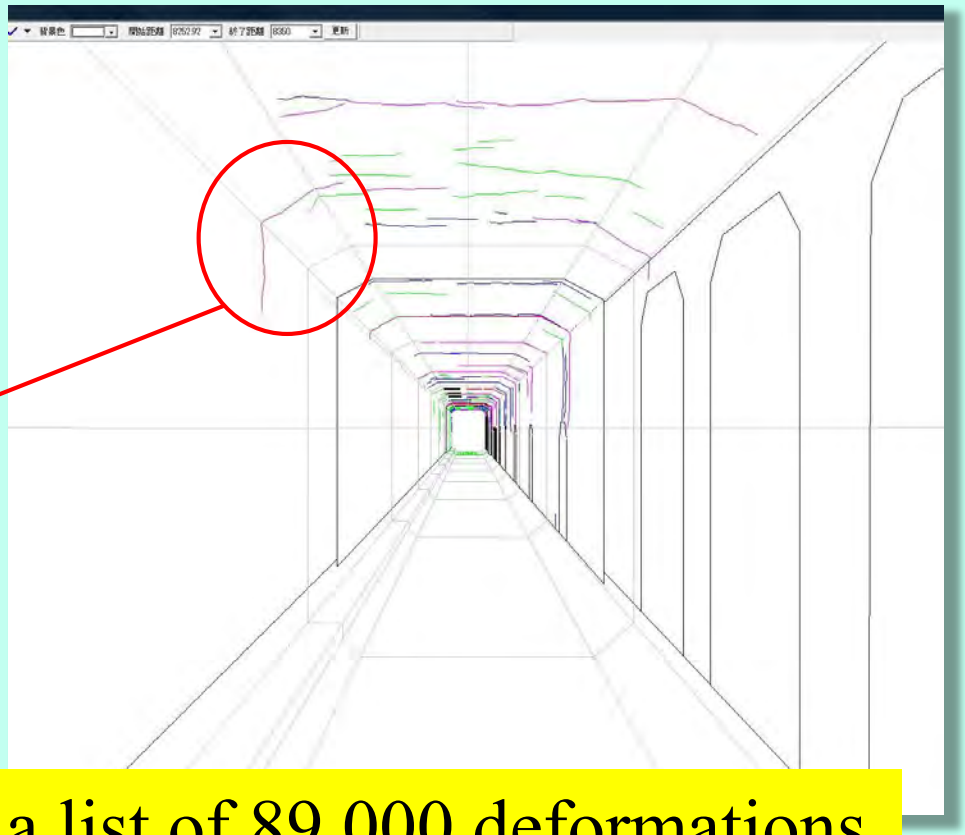


Corrosion of reinforcing bar in the slab



Tokyo Metro Tunnels (Deformation)



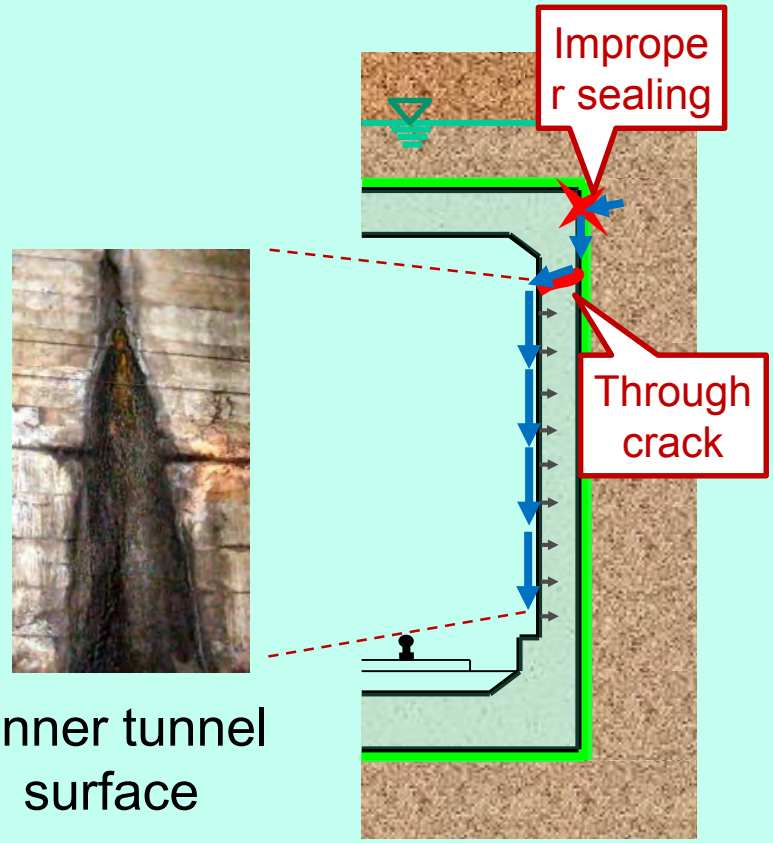


Tokyo Metro manages a list of 89,000 deformations

- Many deformations are minor, but in some sections (such as those suffering from salt damage) concentrated deformation is more major.

Tokyo Metro Tunnels (Deformation)

Deterioration of Concrete Members due to Leakage



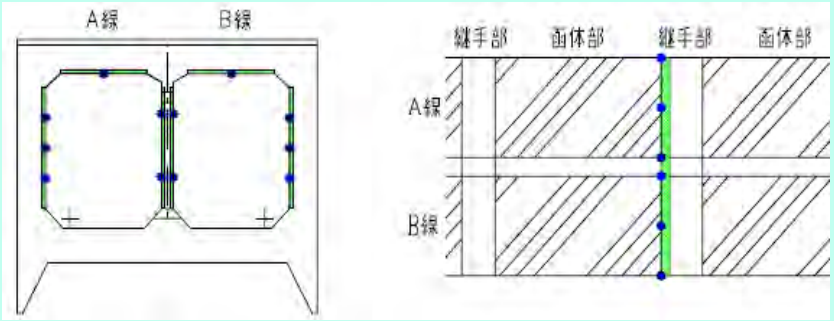
Salt water fills an improperly sealed section or through crack, leaks into a tunnel and chloride ion in salt water infiltrates a concrete surface

Repair Method by Using Sacrificial Anode

The sacrifcial anode is rusted in substitution for a reber

Salt Damage

Caisson tunnels



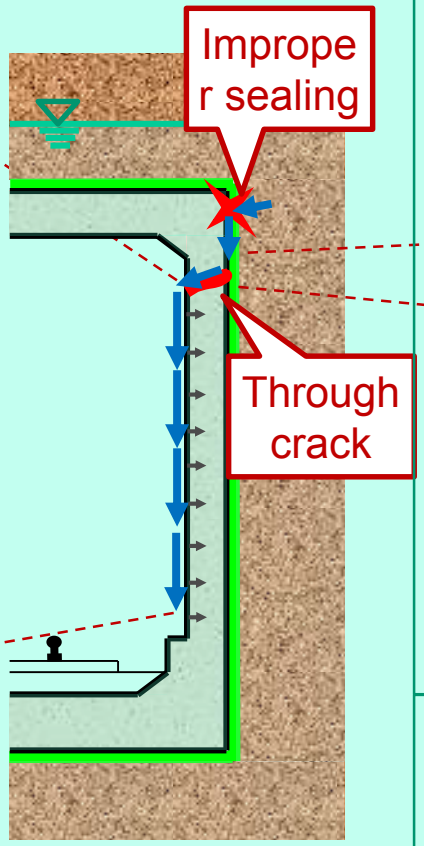
Caisson tunnels

- Leakage of saline water
- Chloride ions infiltrating concrete
- Rebar corrosion

The exposure of rebar and corrosion

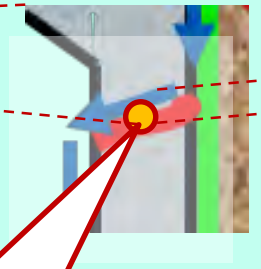
Picture of Salt Damage-1

Inner tunnel surface



(1) Water fills an improperly sealed section or through crack, leaks into a tunnel and infiltrates a concrete surface

(2) When cracks like those in example (1) on the left cross the rebar, they provide a place for highly saline water to leak onto the rebar and corrode it from that location.



Crack crossing with rebar

Localized corrosion and fracturing at the intersection

(3) Sealant not functioning well in a location where construction work was difficult - groundwater infiltrated from outside, and the rebar suffered widespread corrosion.

Improper sealing

Salt Damage

2 Inspection and diagnosis of railway tunnels in Japan

Transition of Maintenance System for Railway structures

- **Old maintenance System(Before 1965)**

Corrective maintenance

Counter the problem after it happen.

Structures were wasted by the Pacific Ware.

No maintenance .(After the War-1965) → **Accidents occurred frequently.**

- **Current maintenance System(After 1965)**

Advance (always) inspection. ← **Extract weak or deformed points .**

↓

Soundness Judgment.

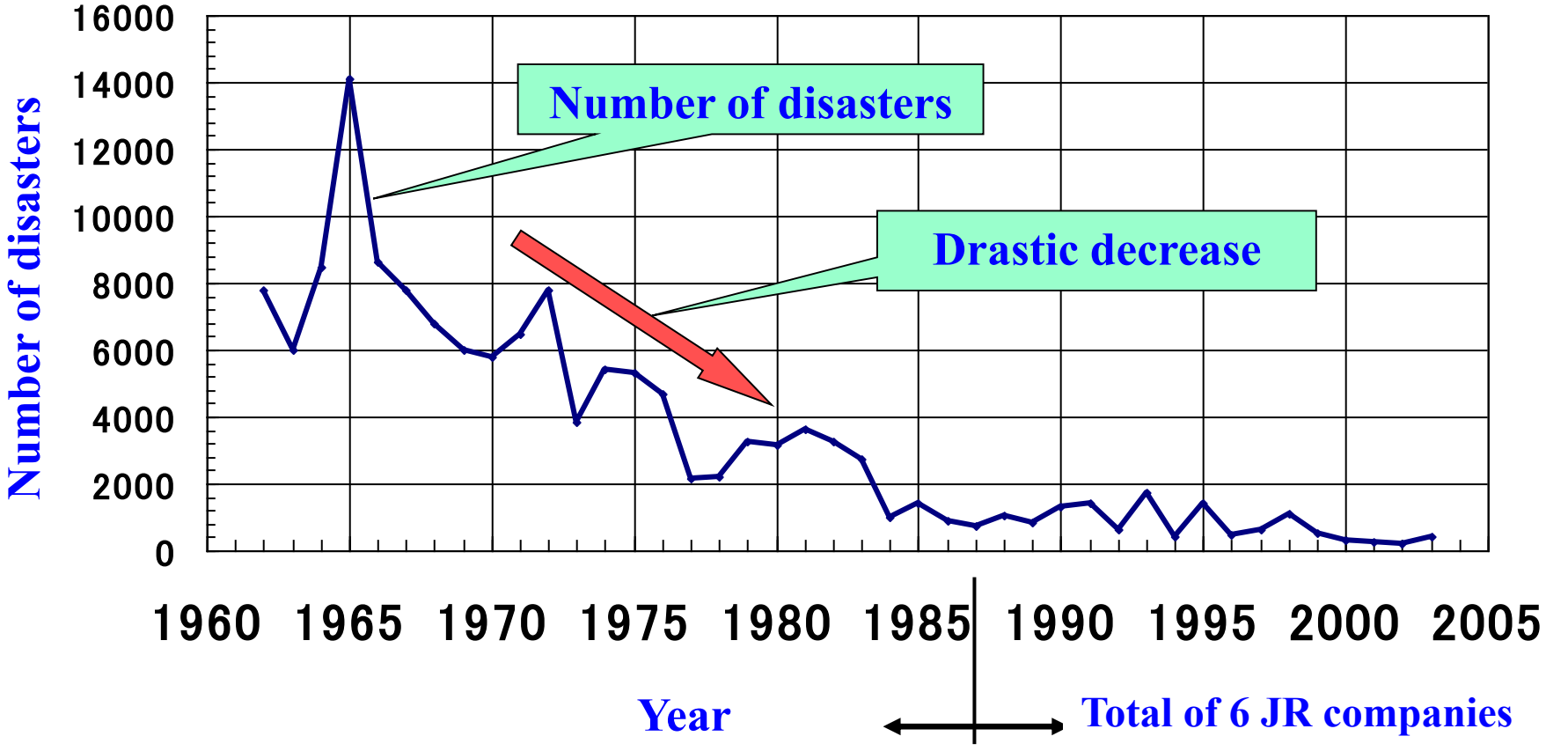
↓

Measures. **(Monitoring or repair work)**

Preventive maintenance

Transition of the number of disasters for Railway

1962－2003



Include accidents

Transition of an approach to maintenance for Railway structures

Before 1965 — Corrective maintenance

After 1965 — Introduce preventive maintenance
(Inspection, Soundness judgment, Measures)

1973 — Enacted the standard for replacement

1975's — Maintenance -free (High performance concrete, Bare steel)

About 2008 — Problems of Carbonation and spolling

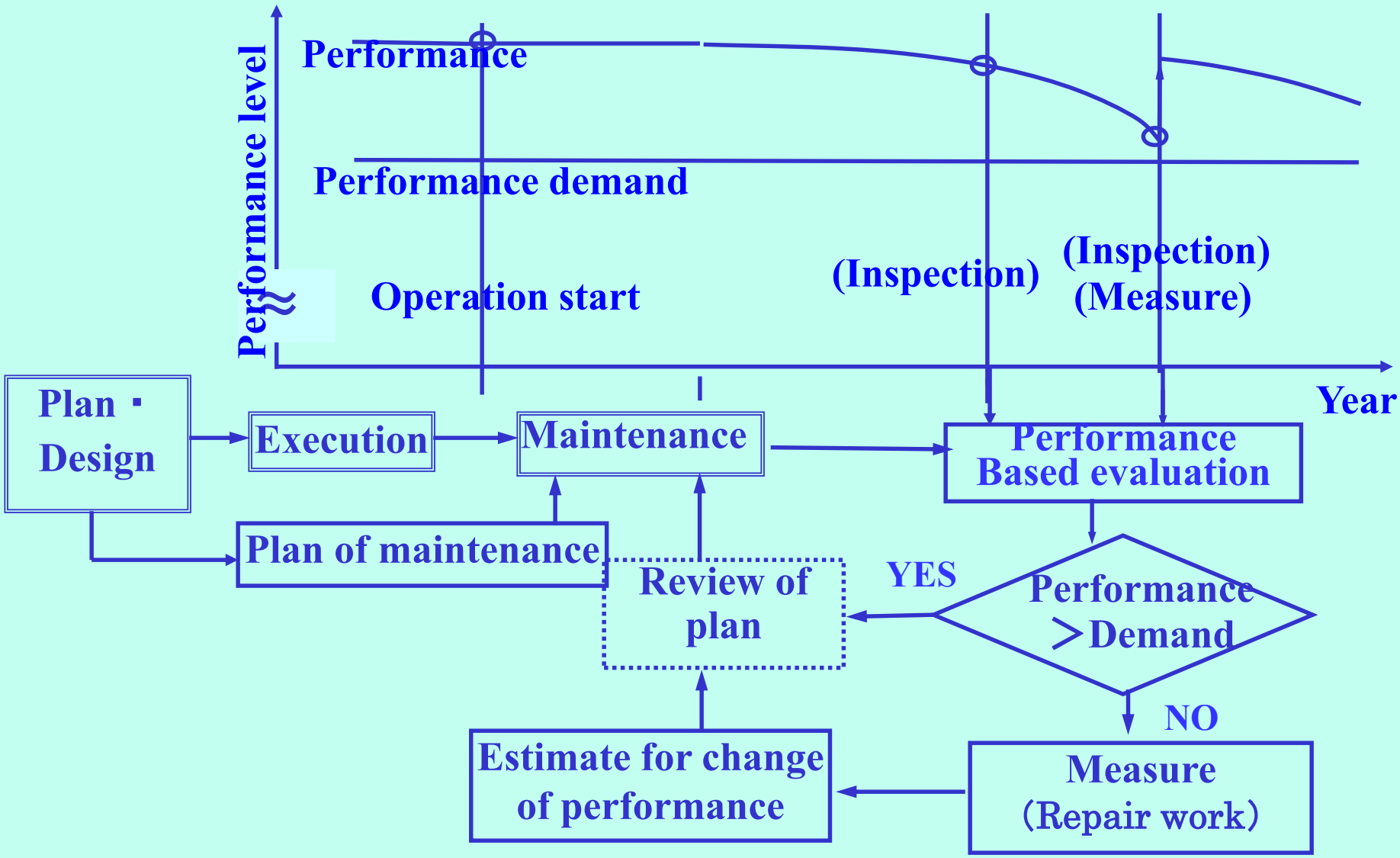
Consider structure to use for 100 years

Now — Minimum maintenance

Efficient maintenance.

Combined preventive maintenance with corrective maintenance.

Maintenance in the performance based design system

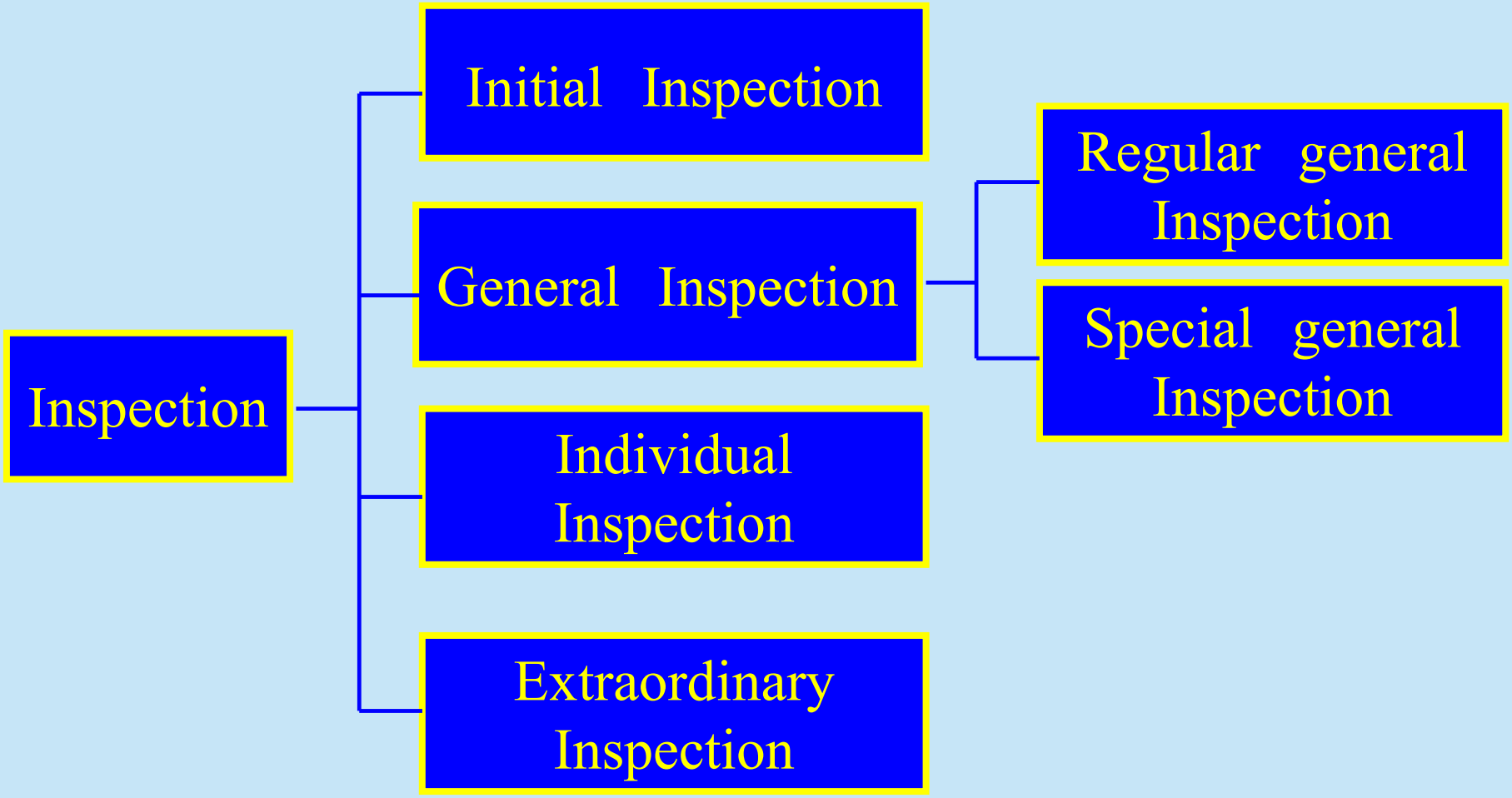


Keep performance by design, execution and maintenance

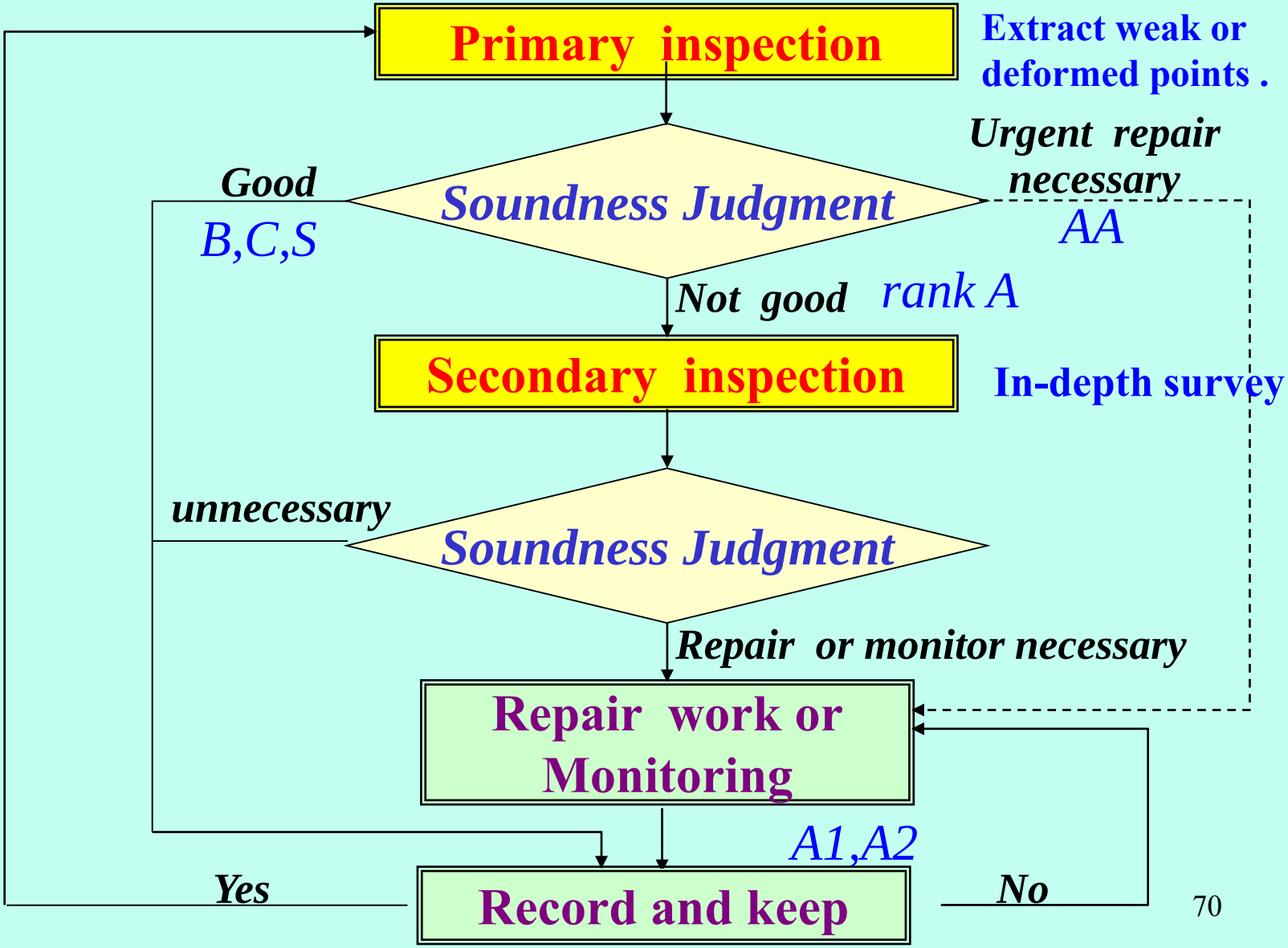
Examples Performances and Performance Items for Tunnels

Required Performance	Performance Item	Examples of Verification Indices
Safety	Stability of tunnel structure	Collapse of tunnel
	Margin between clearance gauge and tunnel lining	Clearance gauge
	Stability of roadbed section	Upheave/settlement/displacement of roadbed
	Safety against spalling	Spalling off of concrete fragments, repair materials, etc.
	Safety water leakage/freezing	Water leakage/freezing
Serviceability	Serviceability against water leakage/freezing	Water leakage/freezing
	Dirtying of surfaces	Dirt that significantly interferes inspection
	Affect on surrounding environment	Harmful affect on surrounding environment
Restorability	Restorability during a disaster, etc	Tunnel collapse

Inspection Categories for Structure

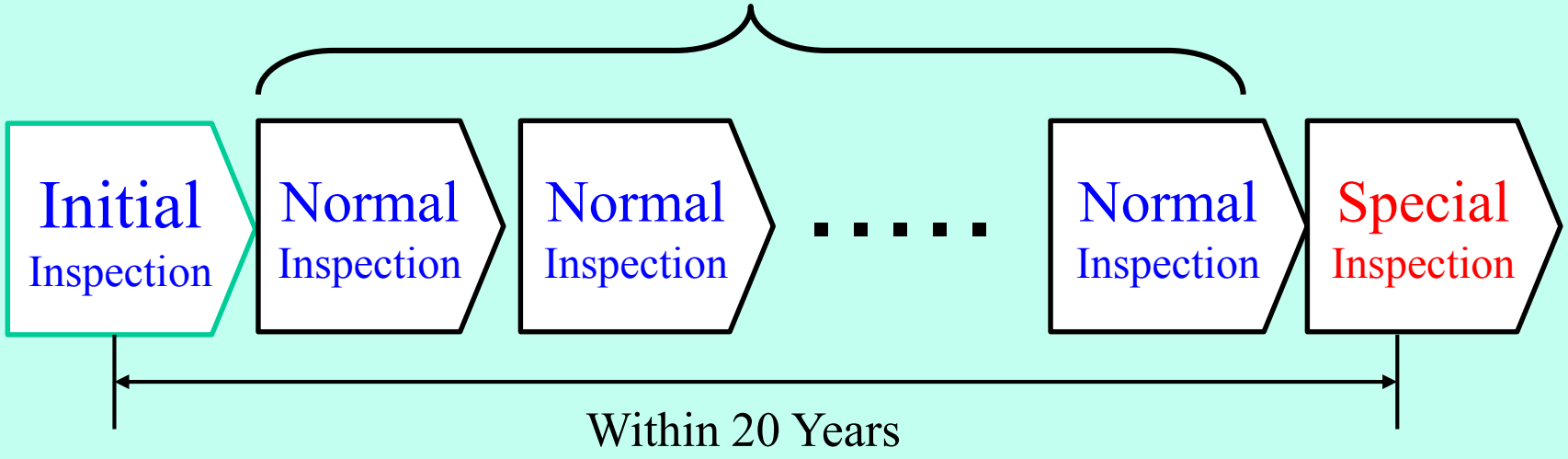


Flow chart of tunnel maintenance



Every 2 Years

- **Presence / absence of deformations**
- **Understanding of their progression**



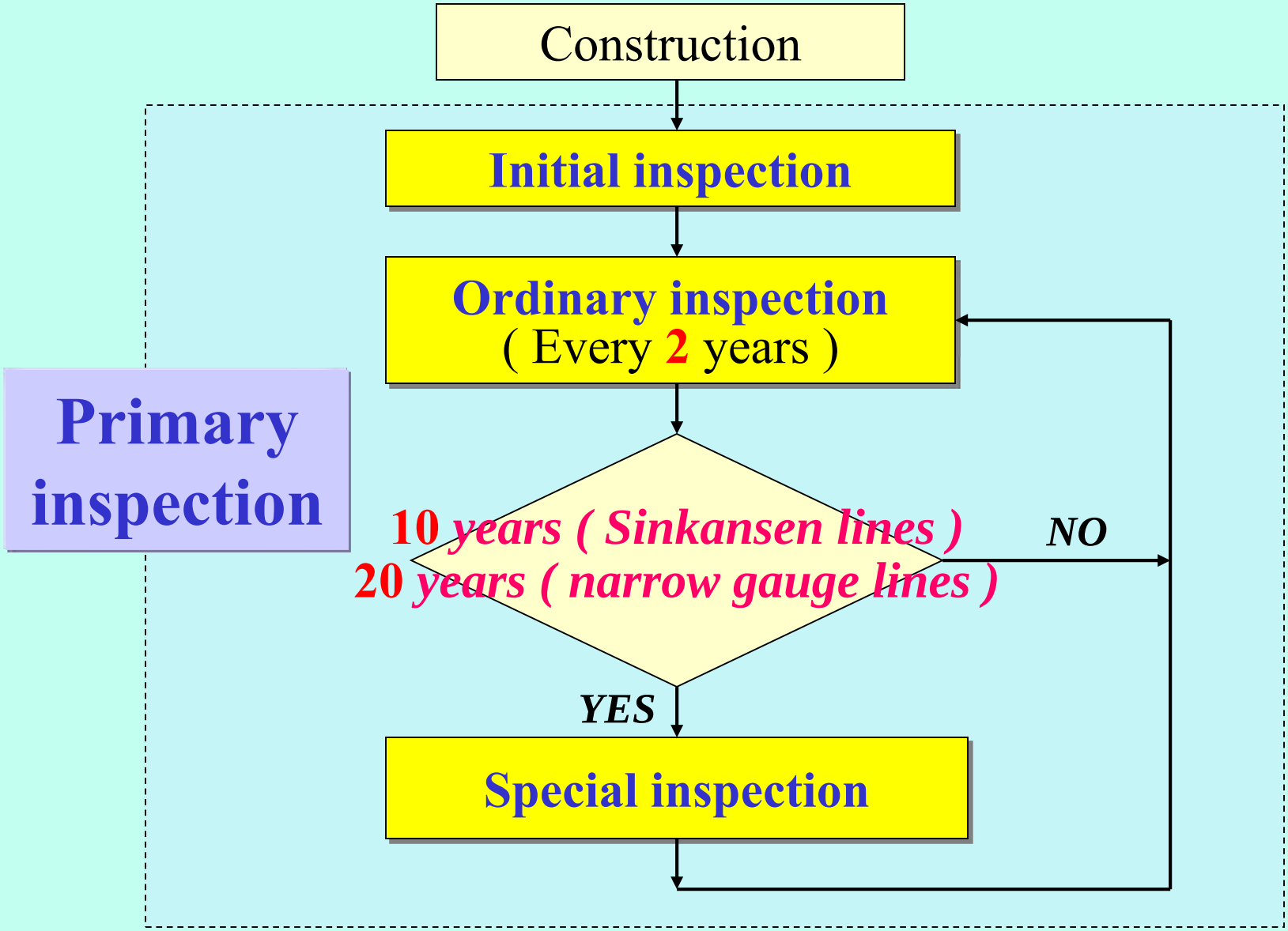
- **Before launching operation**
- **Understanding of initial conditions**

- **Increase precision of grading**

Visual inspections are the main survey method for normal inspections by rule of the Ministry of Land, Infrastructure and Transportation.

Inspections

Classification of Primary inspection



Contents of Inspection

Inspection		Purpose	Inspection interval	Item of inspection	Soundness
Initial Inspection		Understand the initial state of the structure	New construction, Reconstruction	Carefully observation +α if necessary	Divide into A･B･C･S For spalling, Divide into α･β･γ
General Inspection	Regular	Extract the deterioration of the structure	2 years	Observation	
	Special	Improve the precision of judgment of Soundness	20 years	Carefully observation +α if necessary	
Individual Inspection		Presume causes of the deterioration , estimate the deterioration, check of the performance demands	–	Carefully observation Detail investigations	Divide A into subdivisions
Extraordinary Inspection		Put into effect, when it needs.	–	Observation +α if necessary	Divide into A･B･C･S For spalling, Divide into α･β･γ

3 Primary inspection

Inspection methods of railway tunnels

>Observation Photograph

>Measurement of cracks

>Measurement of tunnel deformation
(Inner section, convergence and leveling measurement)

>Investigation of lining thickness and behind ground
(Nondestructive inspection, Destructive inspection)

>Material testing

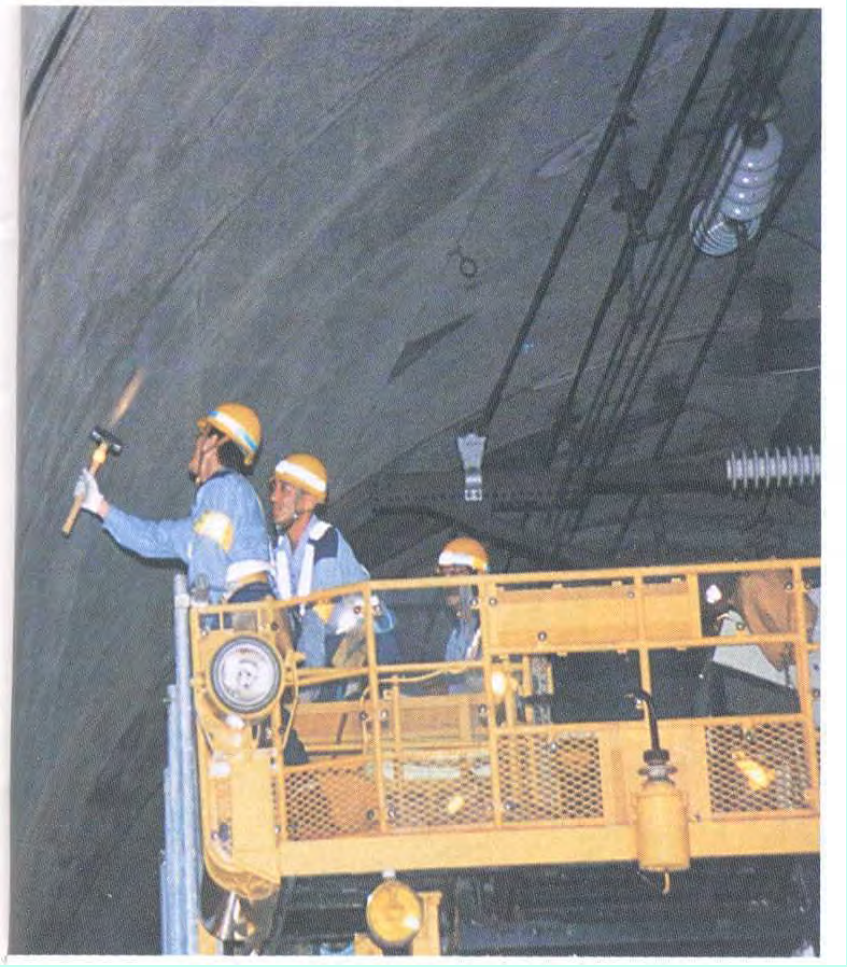
>Underground displacement measurement

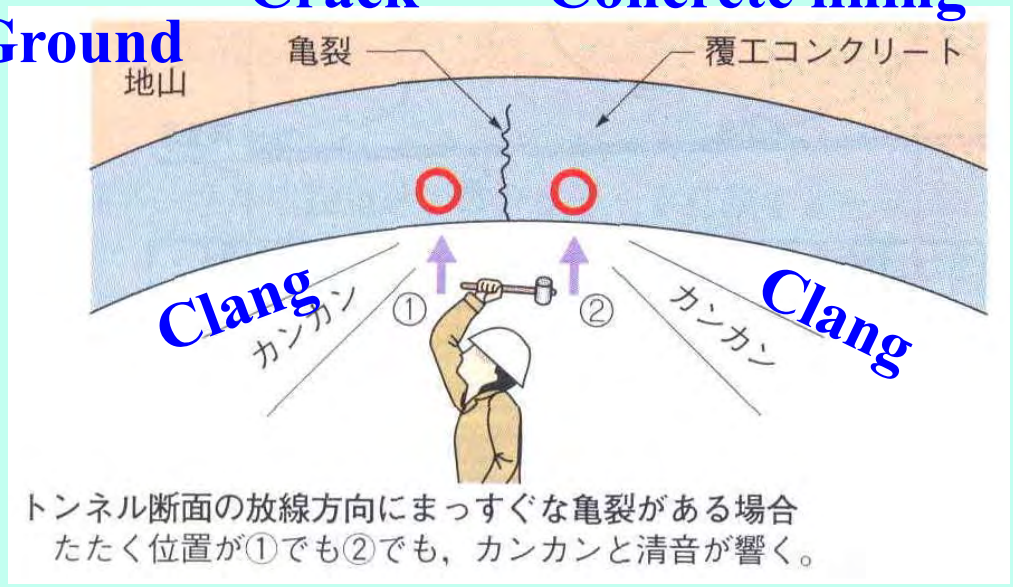
>Measurement of lining strain

>Etc.

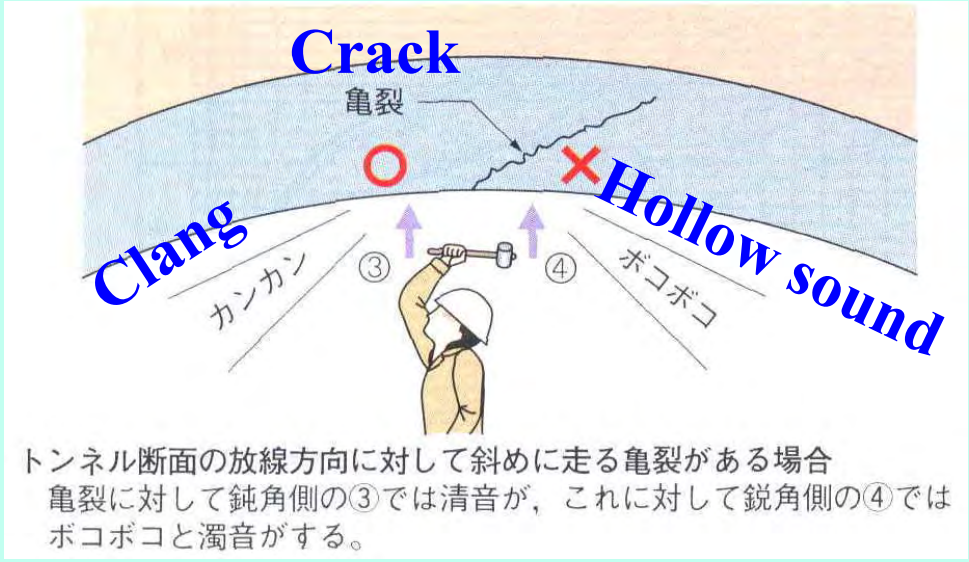
Hammering
(Primary inspection)

※日経コンストラクションより





トンネル断面の放線方向にまっすぐな亀裂がある場合
たたく位置が①でも②でも，カンカンと清音が響く。



トンネル断面の放線方向に対して斜めに走る亀裂がある場合
亀裂に対して鈍角側の③では清音が，これに対して鋭角側の④ではボコボコと濁音がする。

Regular general Inspection（Tunnel, Observation）

Lighting

Box-tunnel —Observation

Upper slab—Observation

Basis Observation

If necessary, observation from near and hammering.

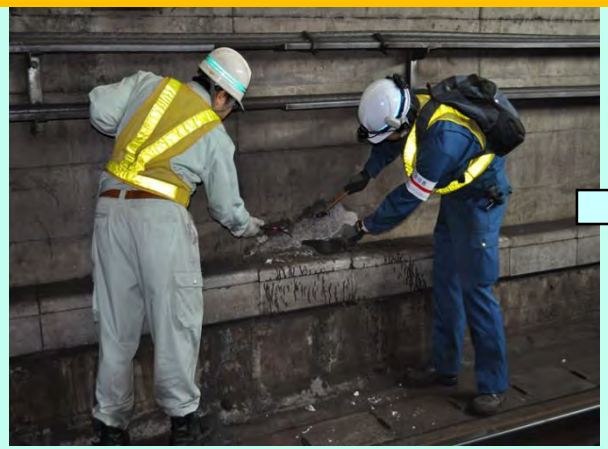
Regular general Inspection
（Tunnel, Hammering, Hit down）

Hammering on side walls

Hammering on lateral of segmental lining

Measurement of clack width.

- **For spalling, hit down at that time.**
- **If impossible, hit down later day.**



78

Special general Inspection

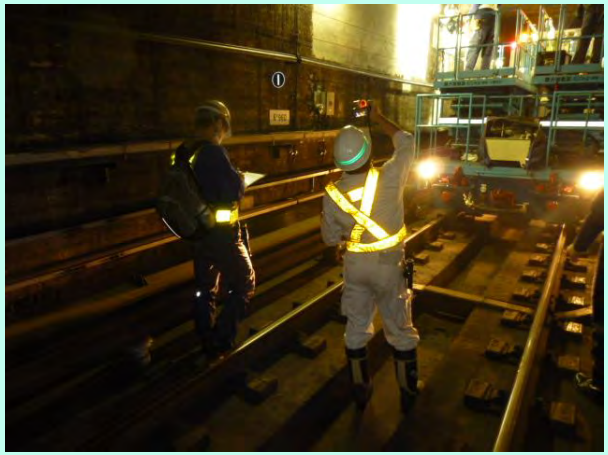
High place working vehicle

Box tunnel

Observation from near, Hammering

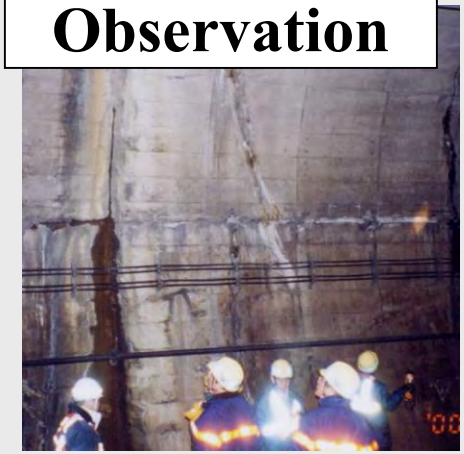
Sign by a piece of chalk

Entry, Take a photo



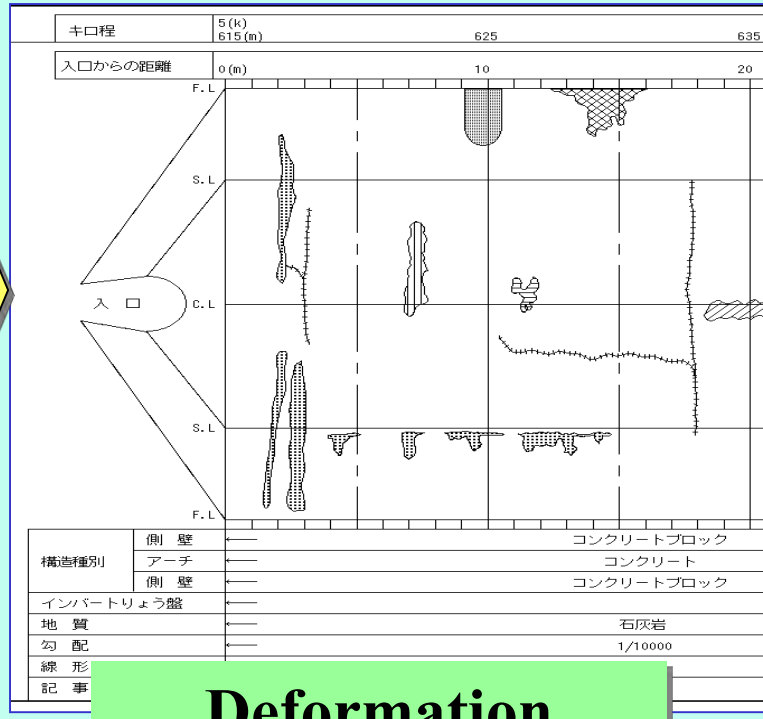
79

Observation



Hammering

Conventional method for primary inspection



Deformation development map

New technologies in practical use

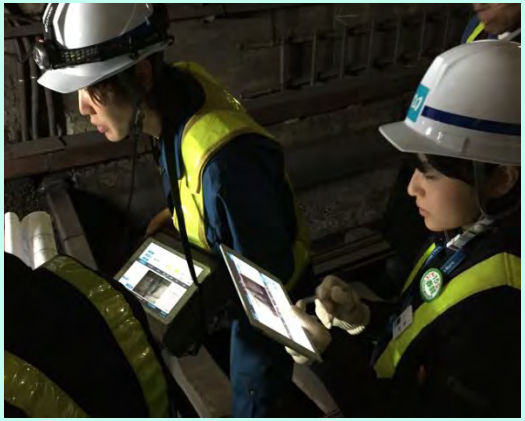
- **Crack measurement system**

  (Line-sensor camera, Laser beam, etc.)

- **Lining separation measurement system**

  (Infrared camera, Lader etc)

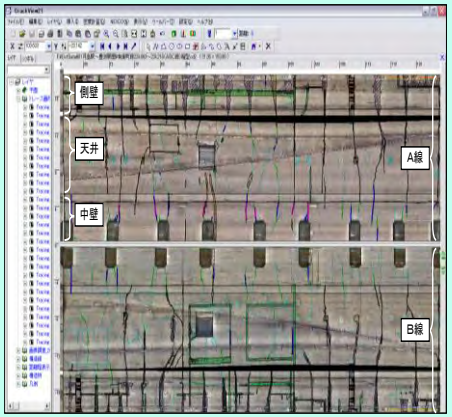
- **Every 2 Years**
- **Visual inspection from tracks**
- **Verify the progression of deformations**
- **Up to 3 months required for completion of each line**



Inspections (Normal Inspections)

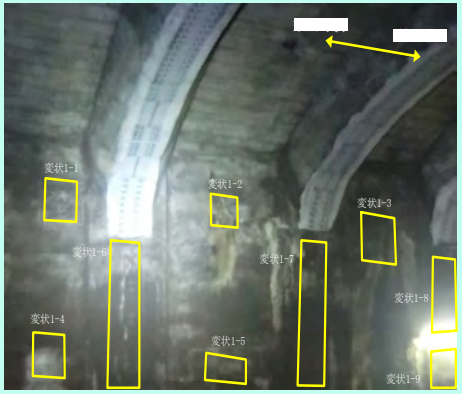
- Every 20 years
- Close visual inspections
- Hammering tests
- 1 year is required for completion of each line

Inspections (Special Inspections)



Visible image photography

Infrared image photography



Naturally, equipment and instruments are also used to help with inspections.

Inspections (Mechanized Inspections)

Health Grade

AA	Urgent Action
A1	Immediate Action
A2	Action at an Appropriate Time
B	Frequent Monitoring
C	Minor Deformations
S	Healthy / Repaired

Structural Deformation Report Record Report

Sorting Number 05T03 A-009
Tozai Line
Submission Date 2013/10/10
Submission Number

Inspection Date YYYY MM DD

Inspection Type	Survey Item
Tunnel Inspectio	Share

Director	Deputy Director	Manager	Person in charge
Kawabata		Takahashi	Arakawa

Structure Name	Structure Control Number
Yamanote 4S Curve 200	Tunnel 53A

Assignee	Inspector
Metro Rail Facilities Co., Ltd.	samu Akiyan

Line	Stretch	Distance from Origin, Location	Rank
A	Between Takadanobaba and Waseda Stations	4K 949m	B

Inspection Method	Visual	Health grade regarding peeling Final/Estimated	β
Deformation Type	Diagonal crack B	CJ B	Peeling B
Description	Diagonal crack, peeling and CJ on left side wall		
Cause	Unclear		
Action	Monitor		

History	Inspection Date			Action and countermeasures to deter aging, etc.	Rank	
	2005	10	7	Deformation report	B	–
	2009	4	15	No progression, no change in rank, continue to monitor	B	β
	2011	4	21	No progression, continue to monitor	B	β
	2013	4	18	No progression	B	β
	YYYY					

Images of Deformations

13T Takada A056

11T Takada A059

Creating deformation report for each A or B rank deformation. One record for each deformation.

- **Tokyo Metro rank each deformation according to its progression.**

Inspections (Health Grade & Report)

therefore;
Streamlines tunnel inspections are necessary

Tunnel Work

(1) Simplify on-site record-keeping

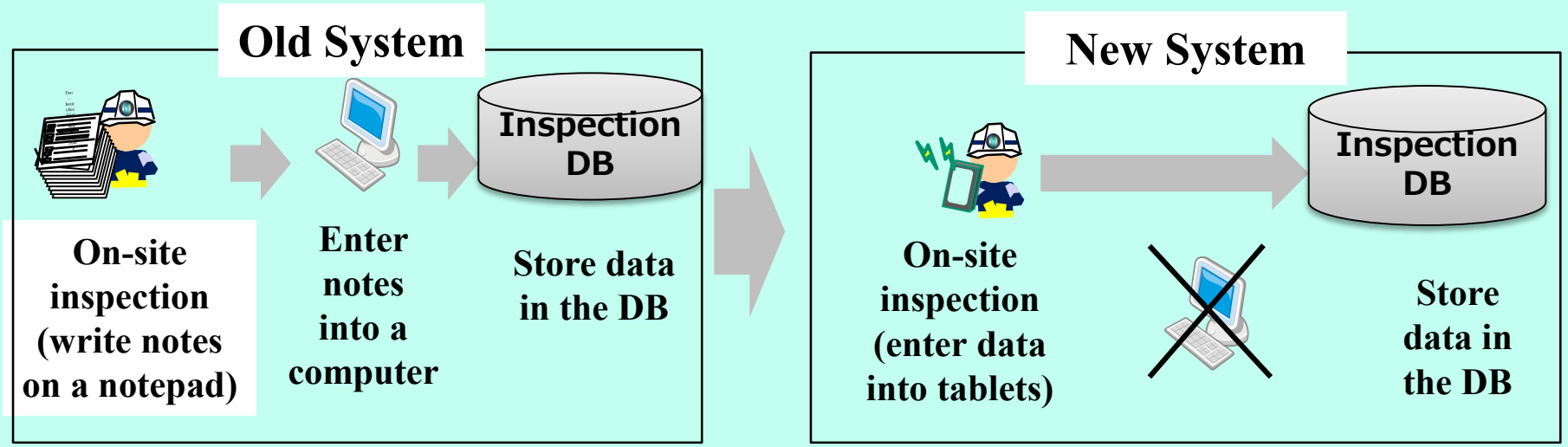
(2) Reduce inspection equipment and paperwork

(3) Remove the need to re-inspect because a deformation was forgotten

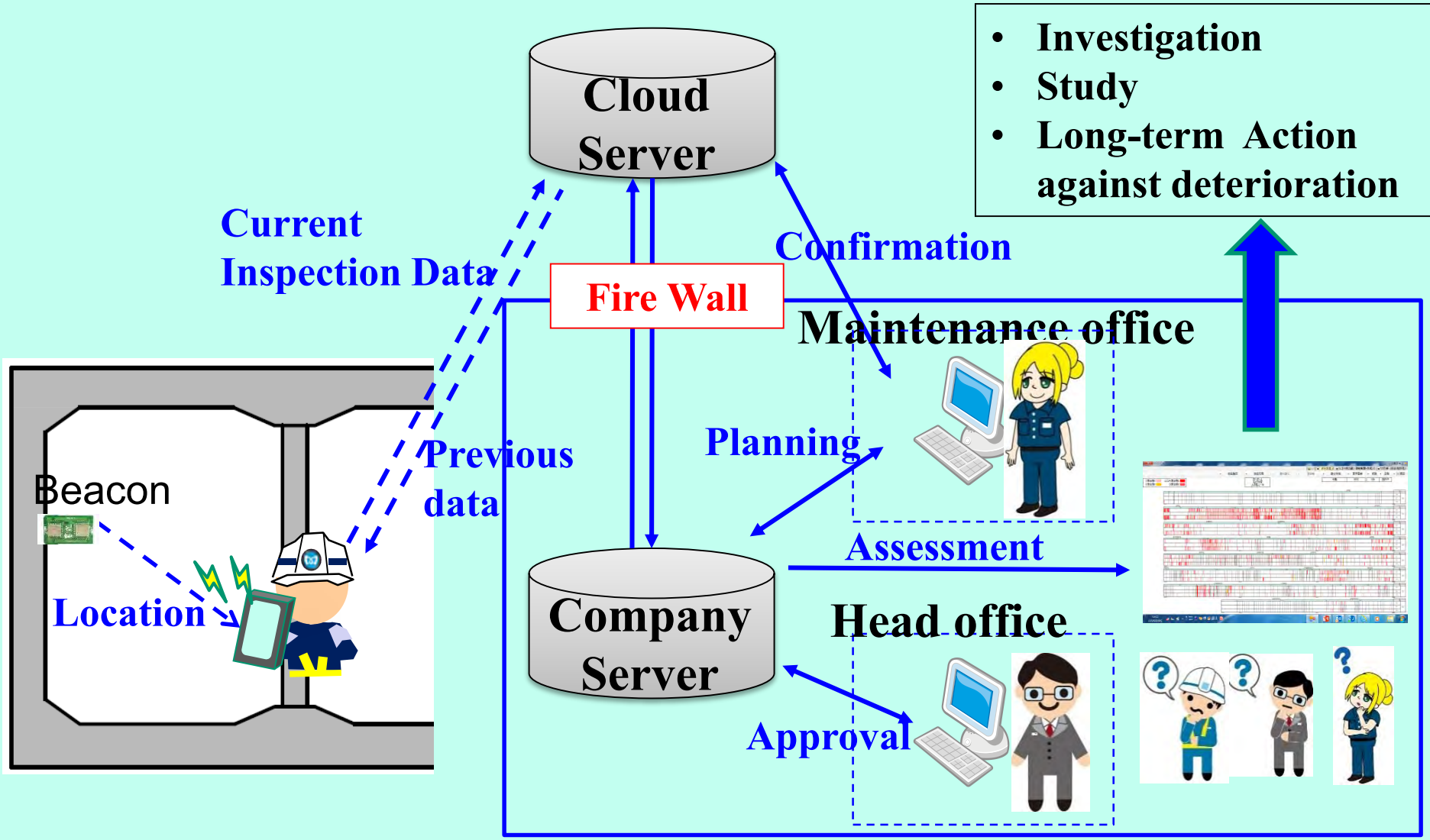
Office Work

(4) Reduce data entry work at the office

(5) Verify and relay inspection data more quickly



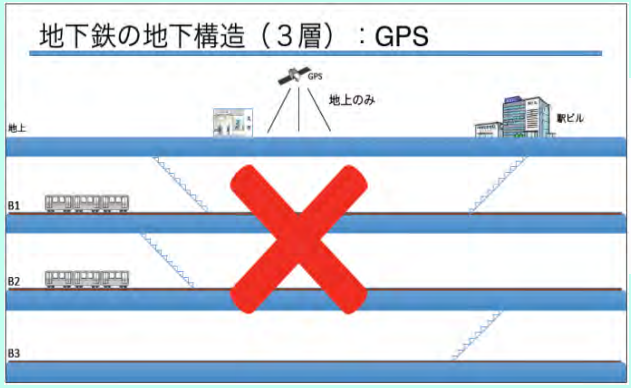
Points on Inspection Efficiency



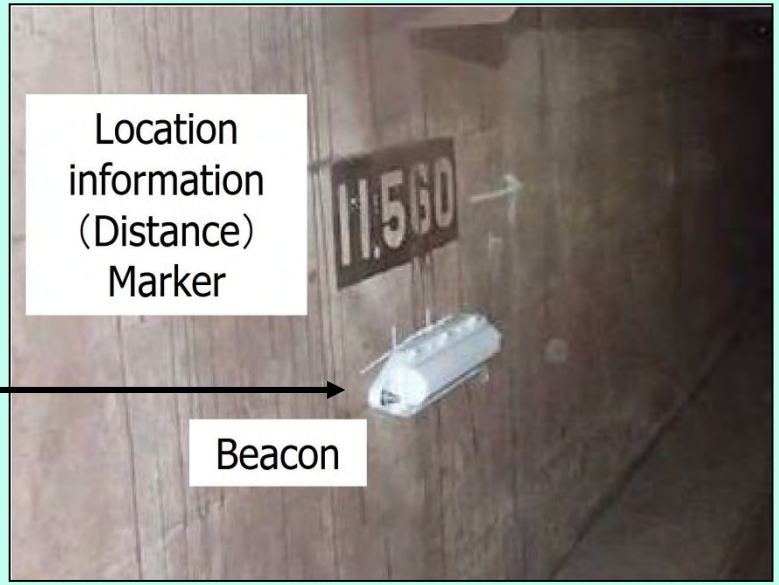
Overview of The System

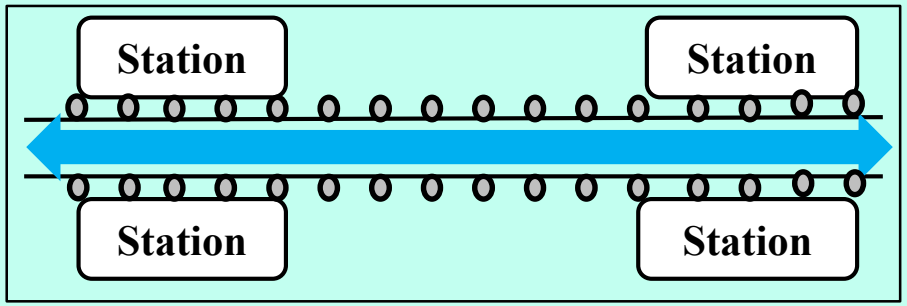
The GPS is not usable in the tunnel under ground

- Beacons installed at 10-meter intervals inside tunnels transmit positional information
- Tablets receive siignal from beacons and caluculate the position.
- Tablets inform inspectors of deformations to inspect based on their location



A beacon Device

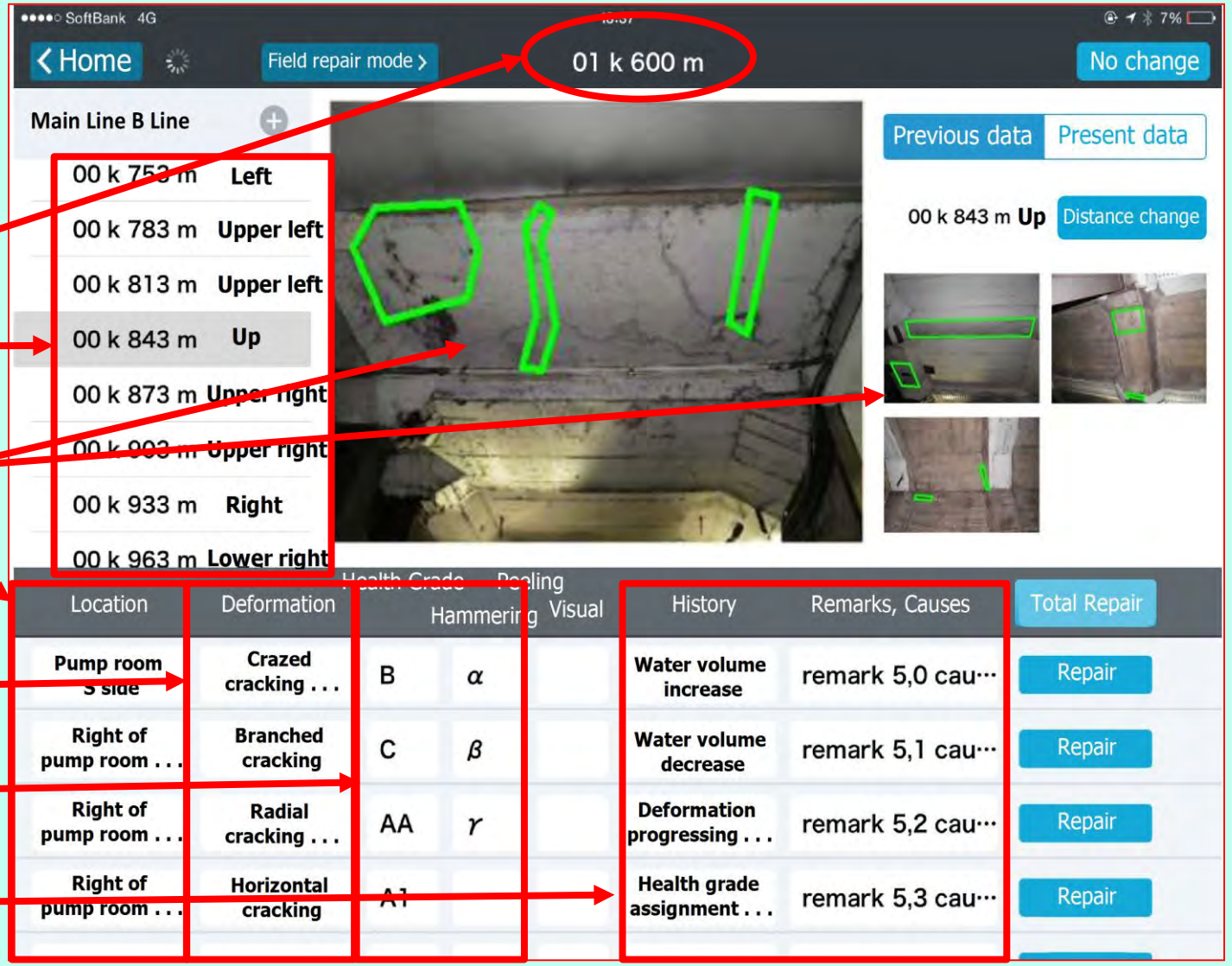




o ・・・Beacon（Every 10 m）

Beacons are placed inside dustproof, waterproof cases attached to tunnel walls

Beacon (Positional Information Acquisition)



Inspector location

Location of existing deformations

Pictures of deformations

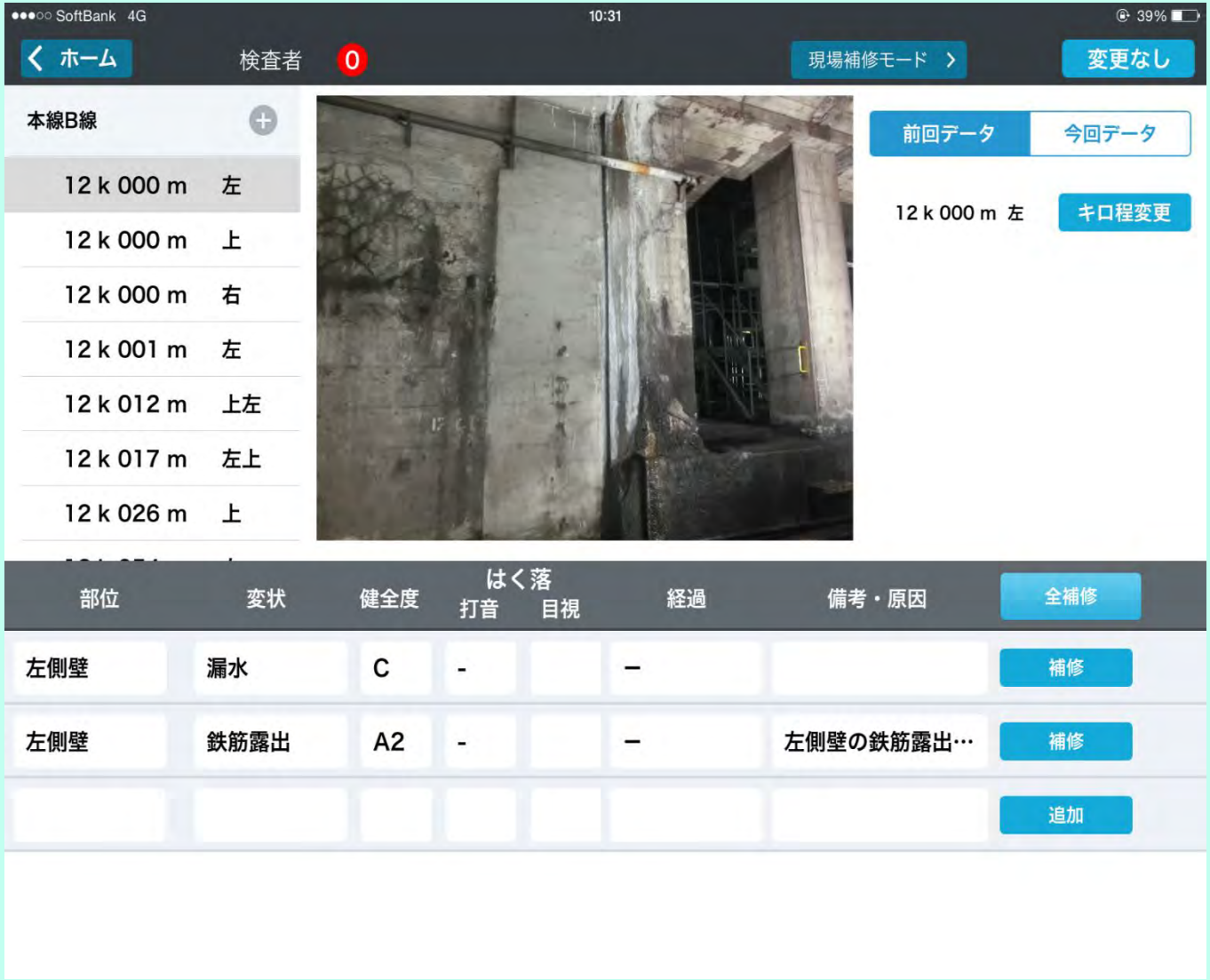
Deformation locations

Deformation types

Deformation rankings

History, remarks

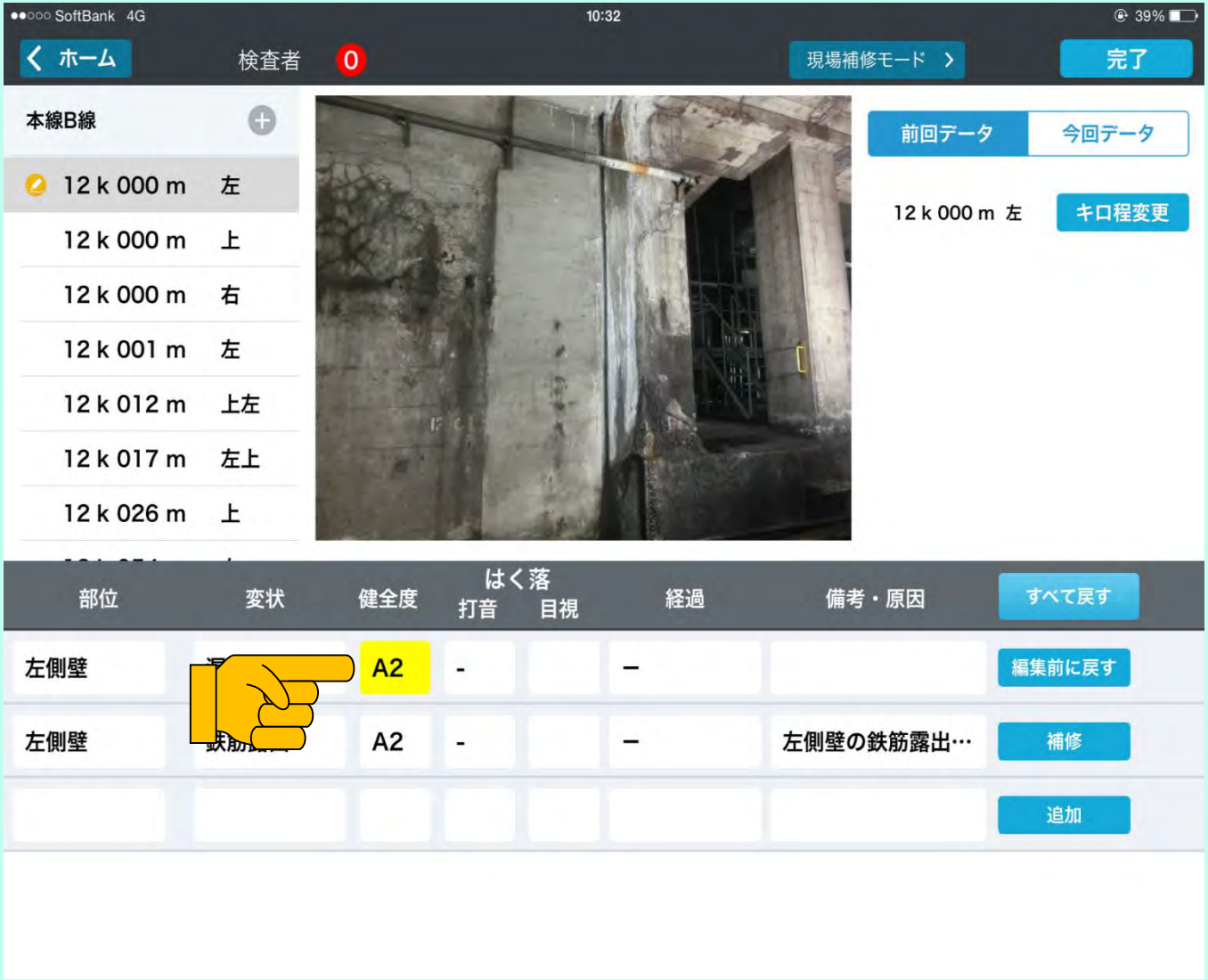
Tablets


SoftBank 4G
10:31
39%
ホーム
検査者
0
現場補修モード
変更なし
本線B線
12 k 000 m 左
12 k 000 m 上
12 k 000 m 右
12 k 001 m 左
12 k 012 m 上左
12 k 017 m 左上
12 k 026 m 上
前回データ
今回データ
12 k 000 m 左
キロ程変更
部位
変状
健全度
はく落
打音
目視
経過
備考・原因
全補修
左側壁
漏水
C
-
ー
補修
左側壁
鉄筋露出
A2
-
ー
左側壁の鉄筋露出…
補修
追加

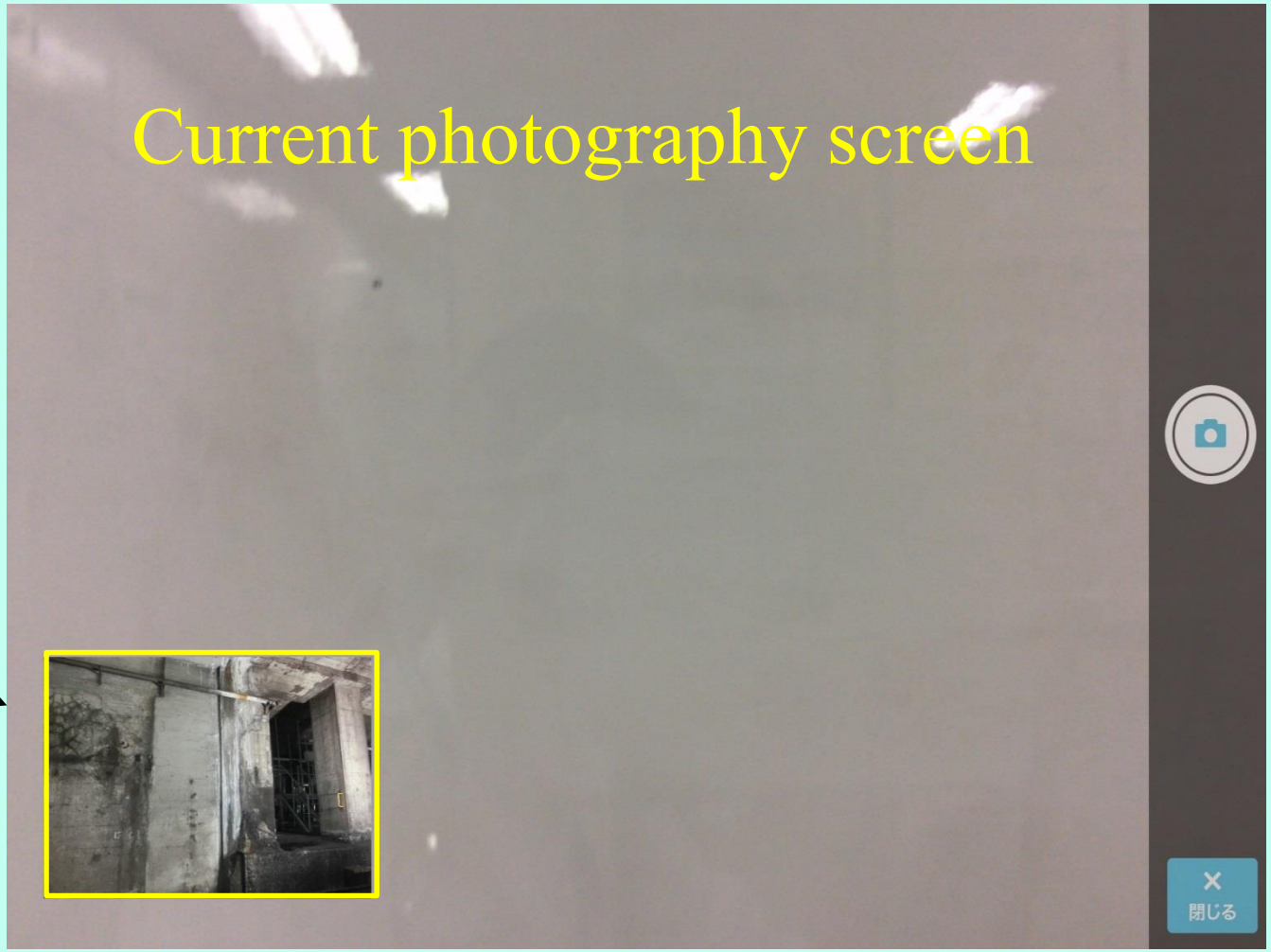
Tablets


SoftBank 4G
10:32
39%
ホーム
検査者
0
現場補修モード
変更なし
閉じる
健全度
AA
A1
A2
A
B
C
S
-

Tablets

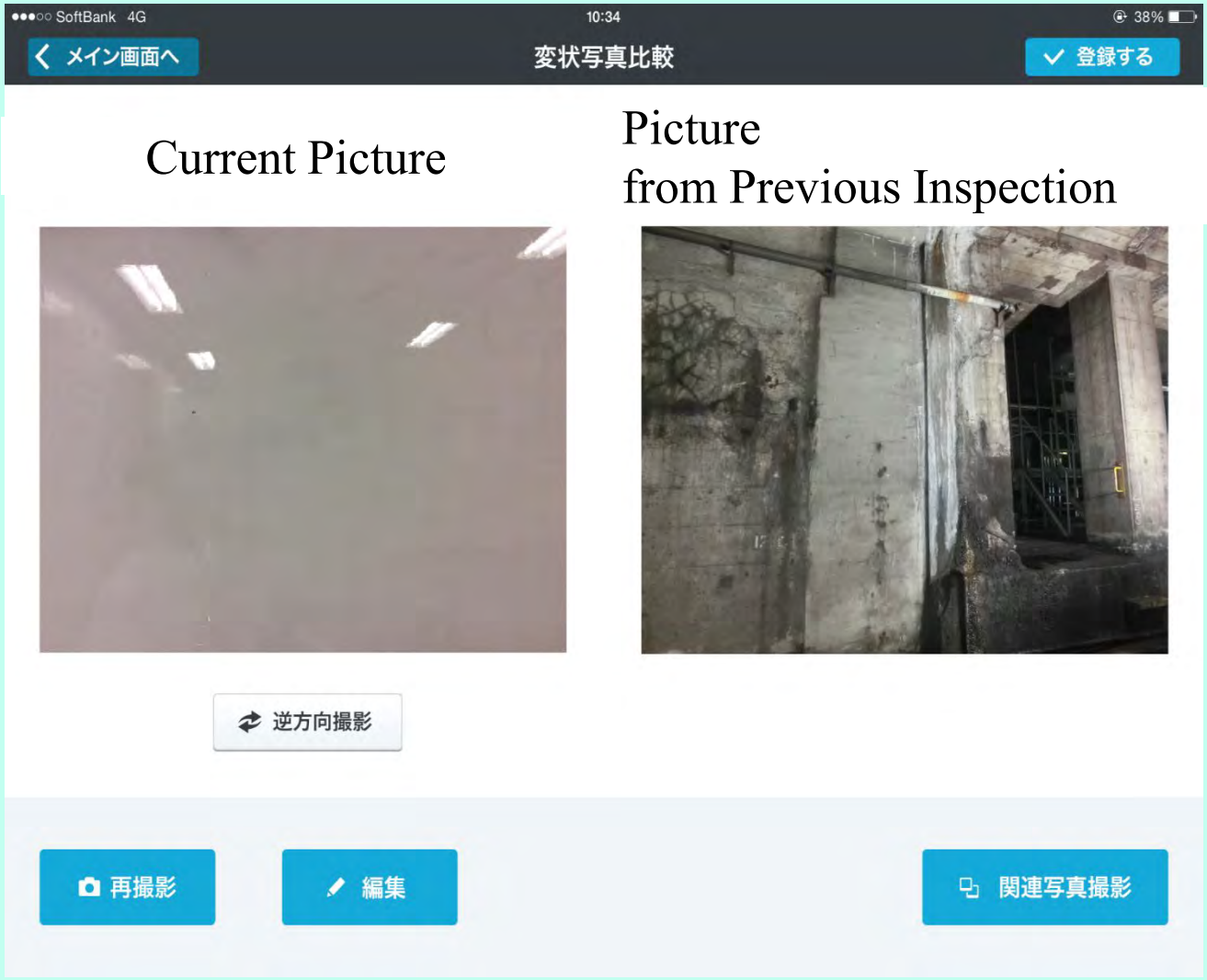

SoftBank 4G
10:32
39%
ホーム
検査者
0
現場補修モード
完了
本線B線
12 k 000 m 左
12 k 000 m 上
12 k 000 m 右
12 k 001 m 左
12 k 012 m 上左
12 k 017 m 左上
12 k 026 m 上
前回データ
今回データ
12 k 000 m 左
キロ程変更
部位
変状
健全度
はく落
打音
目視
経過
備考・原因
すべて戻す
左側壁
A2
-
−
編集前に戻す
左側壁
A2
-
−
左側壁の鉄筋露出…
補修
追加

Tablets

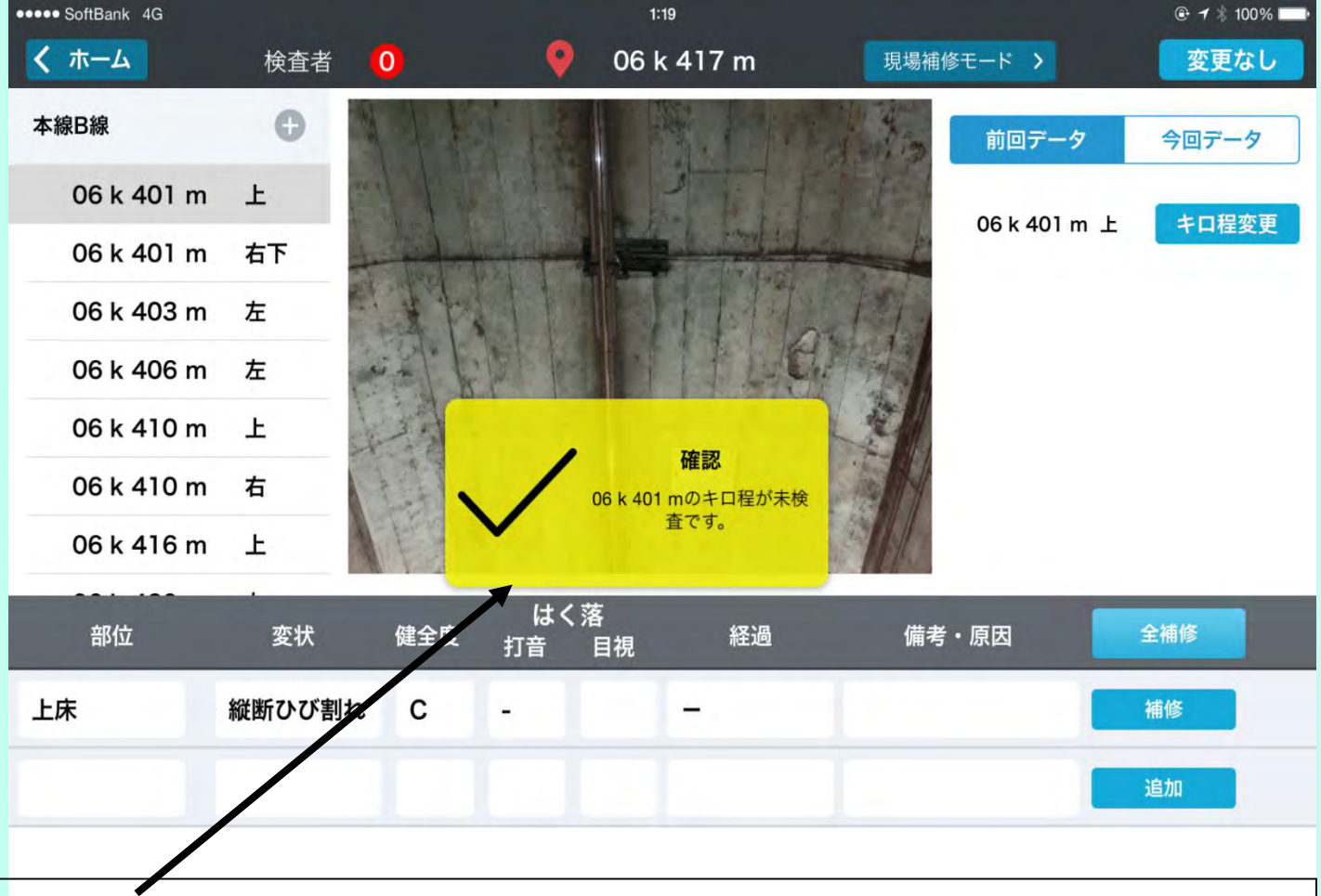


Small Window
Picture of Deformation from Previous Inspection

Tablets


SoftBank 4G
10:34
38%
メイン画面へ
変状写真比較
登録する
Current Picture
Picture
from Previous Inspection
逆方向撮影
再撮影
編集
関連写真撮影

Tablets

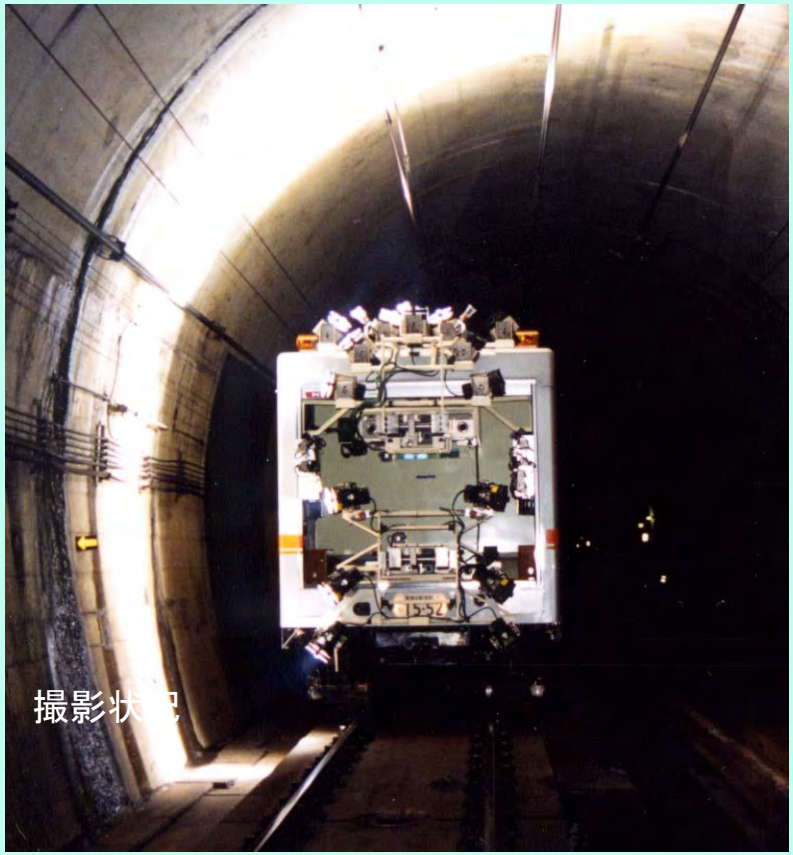


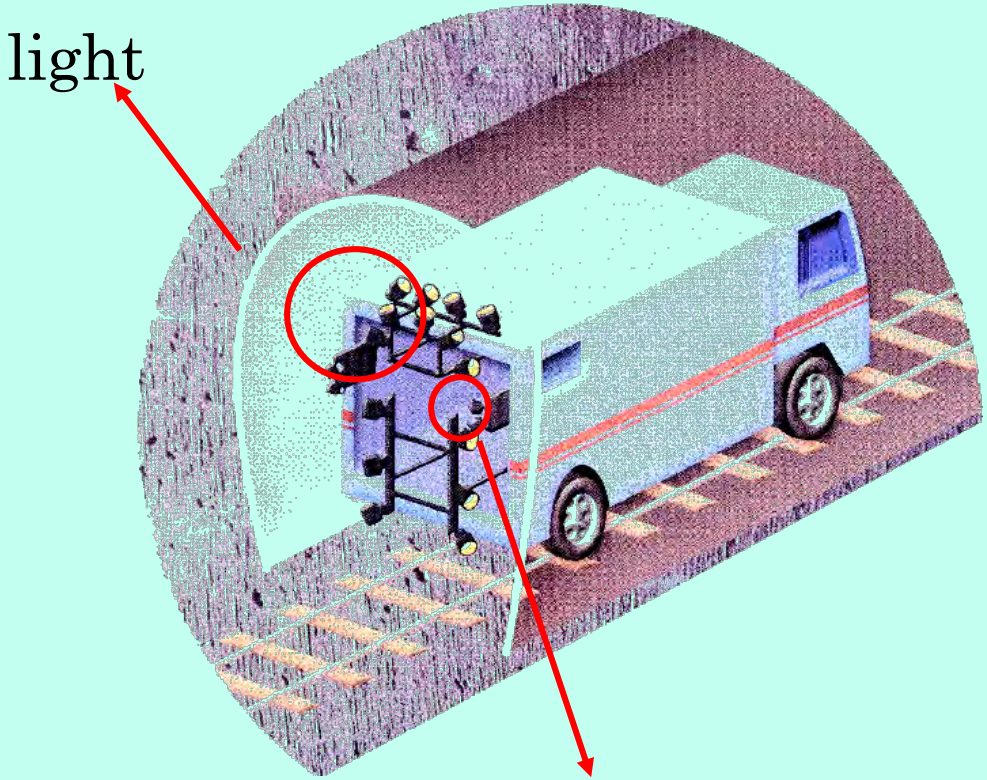
Tablets notify inspectors if they have moved more than 20 meters beyond a deformation without checking it.

Tablets (Oblivion Alert)

Crack measurement system
using line-sensor CCD camera

(JR Central, RTRI)





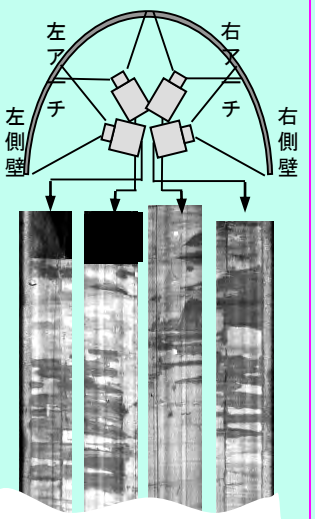
Line-sensor CCD camera

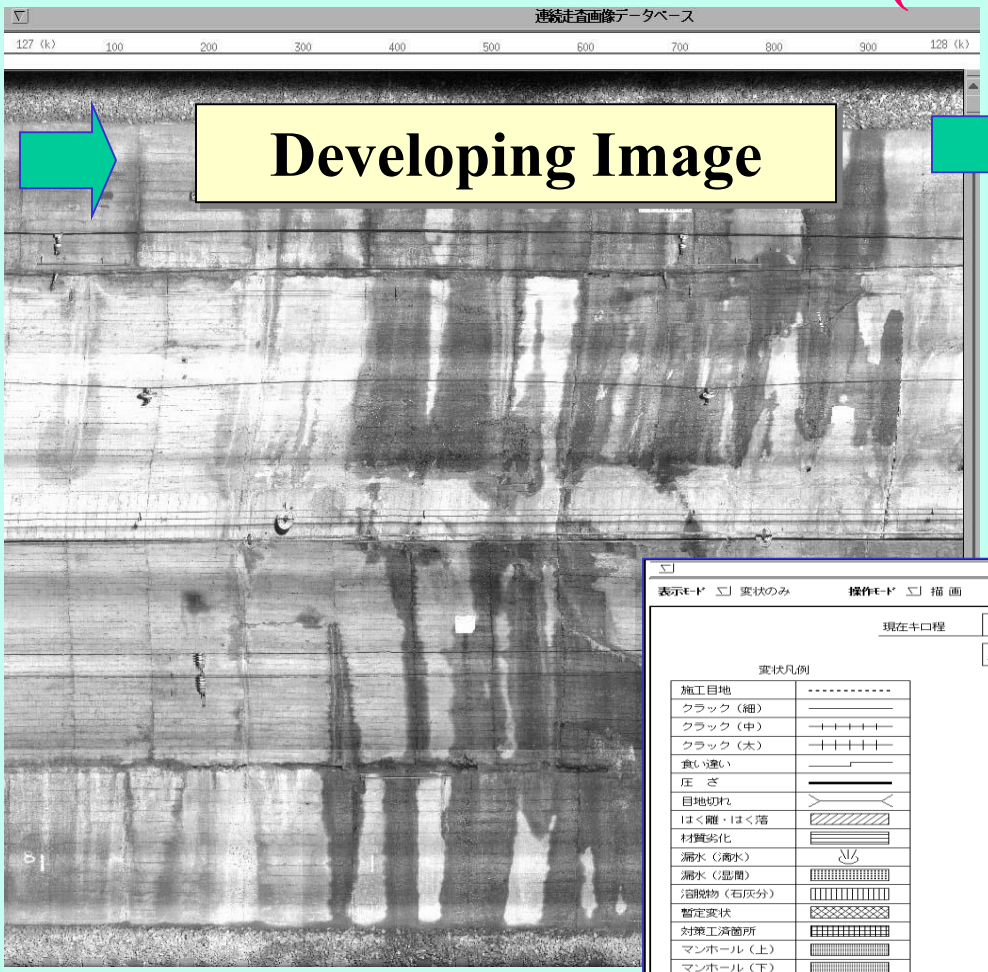
Running speed ：15km/h (single-track tunnel)
Crack accuracy ： 1 mm width

A photo of tunnel lining taken by a line-sensor camera

(JR Central, RTRI)

Photo

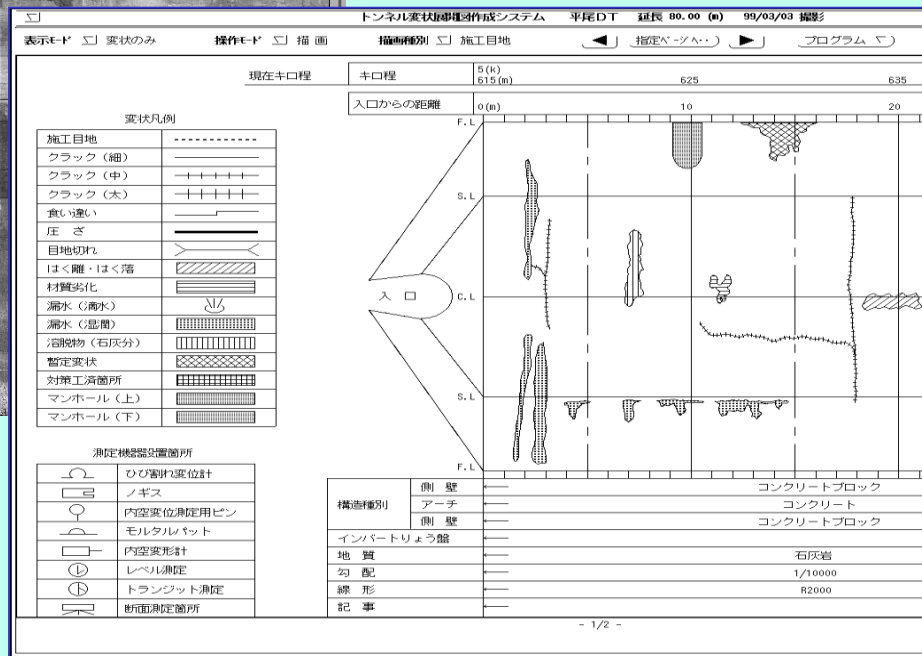




Developing Image

Extraction of crack (1mm), leakage,etc.

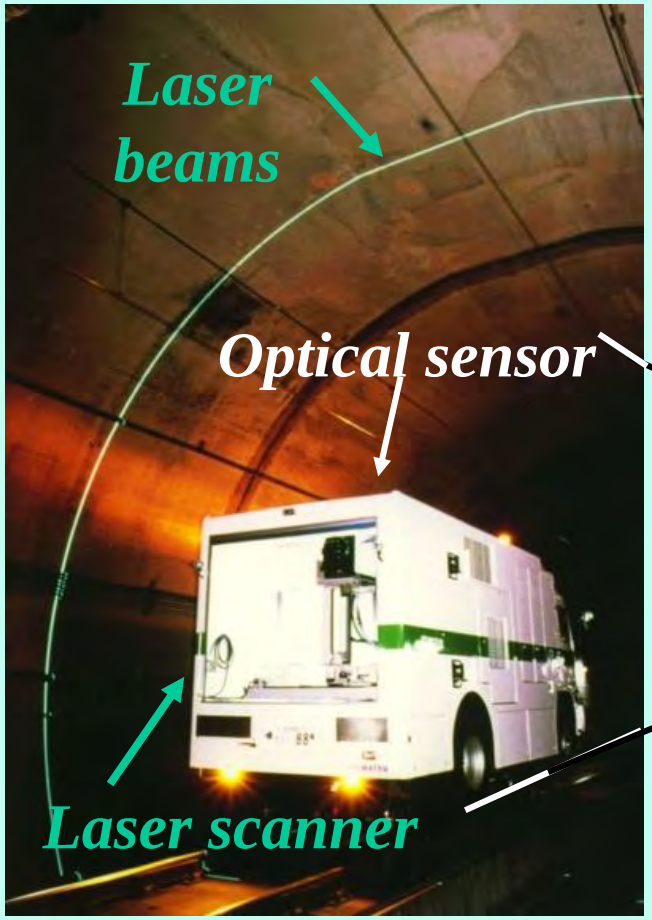
Developing map

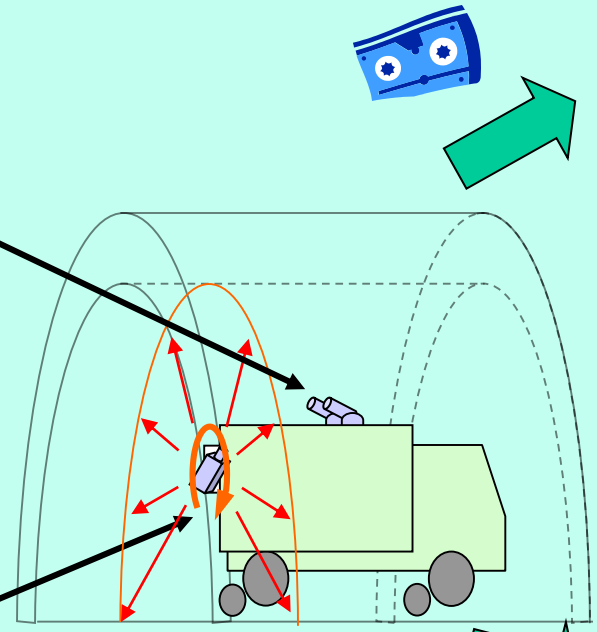


Crack measurement system

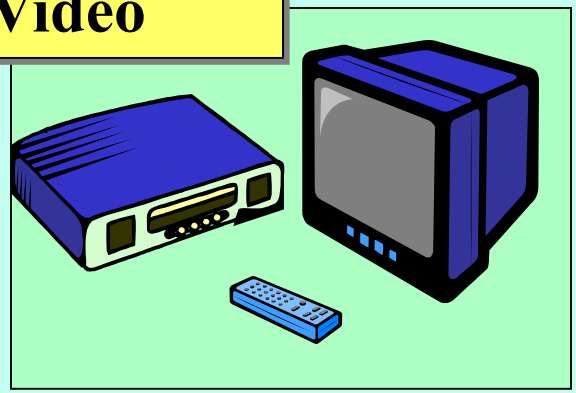
using laser beam (JR East)

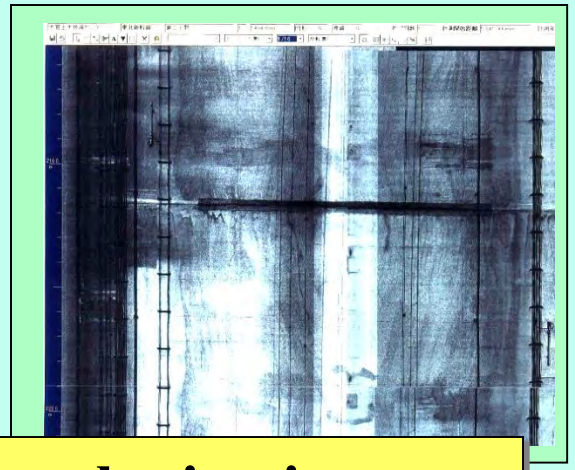
Crack accuracy : 1 mm width





Video

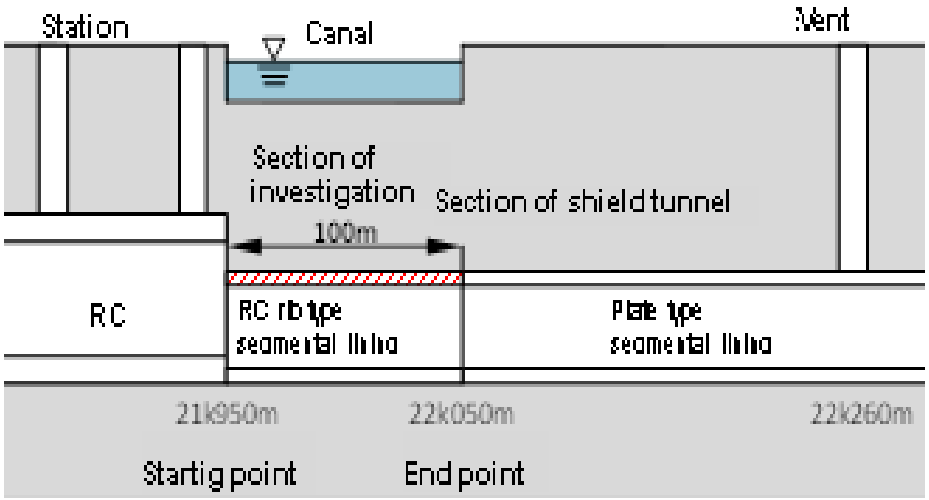




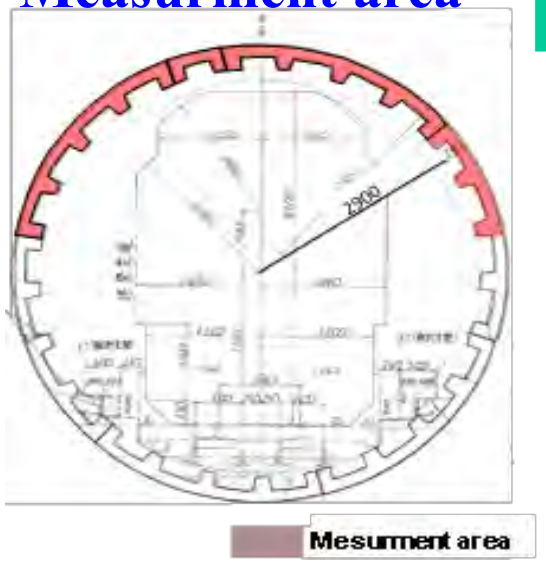
Developing image

Shield tunnel

Section of Investigation



Measurment area



State of movement measurementt

The subject of investigation is 100m part of single-track shield tunnel with RC rib type segmental lining.

4 Secondary inspection

Monitoring methods for deformed tunnels
(and/or for neiboughring construction)

Conventional method

Tape scale

Laser beam

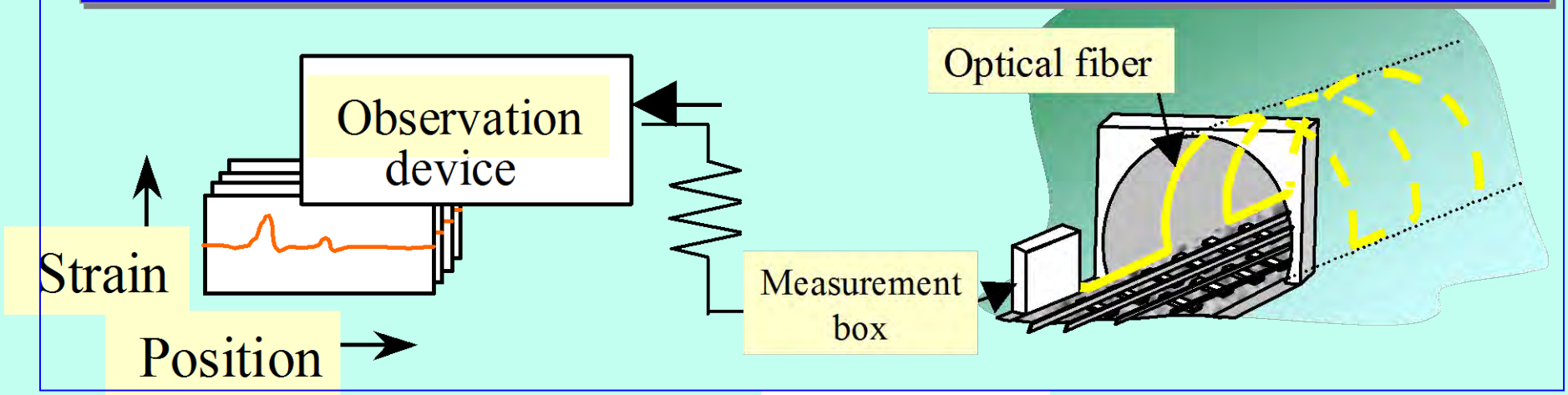
Erectro-optical

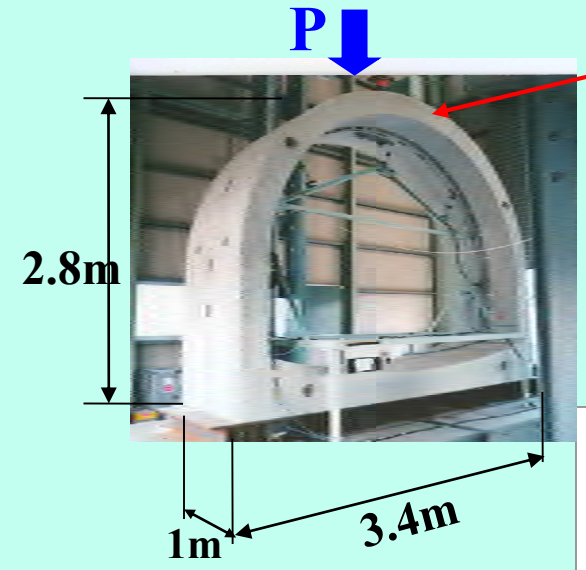
Convergence measurement

Crack width measurement

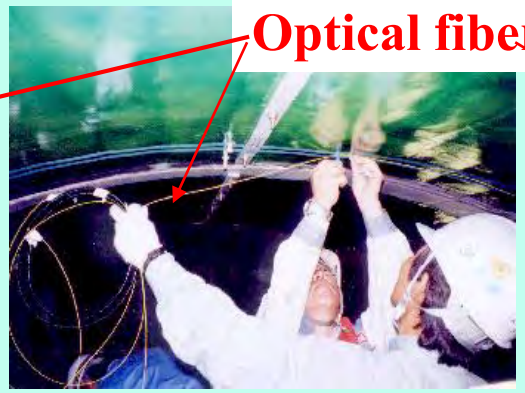
- Optical fiber (RTRI) *under research*
- Electric conductible paint (RTRI) *under research*

Monitoring system by optical fiber (RTRI and MHI)





1/3 model test

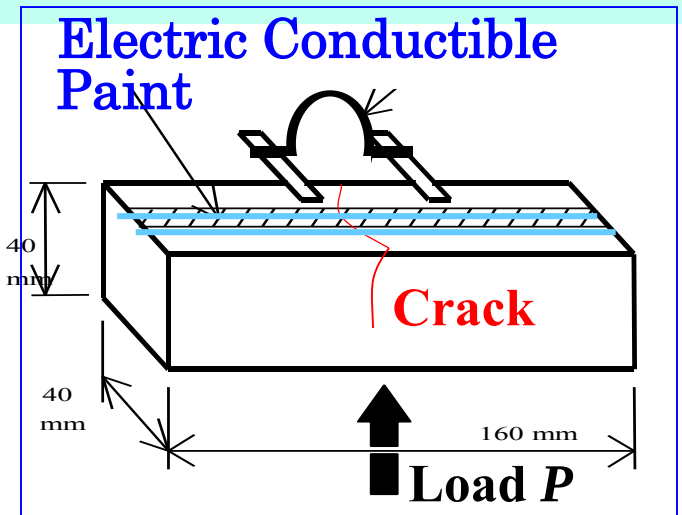


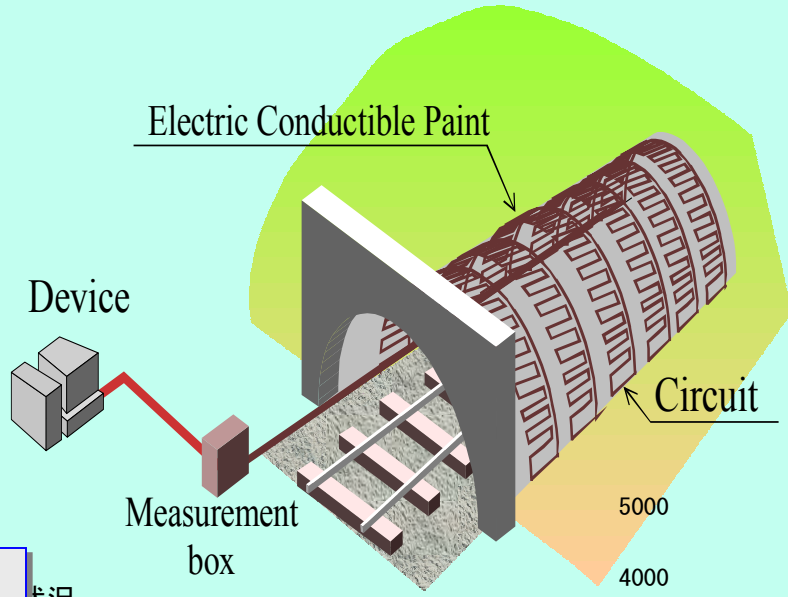
1 Monitoring length = 10km

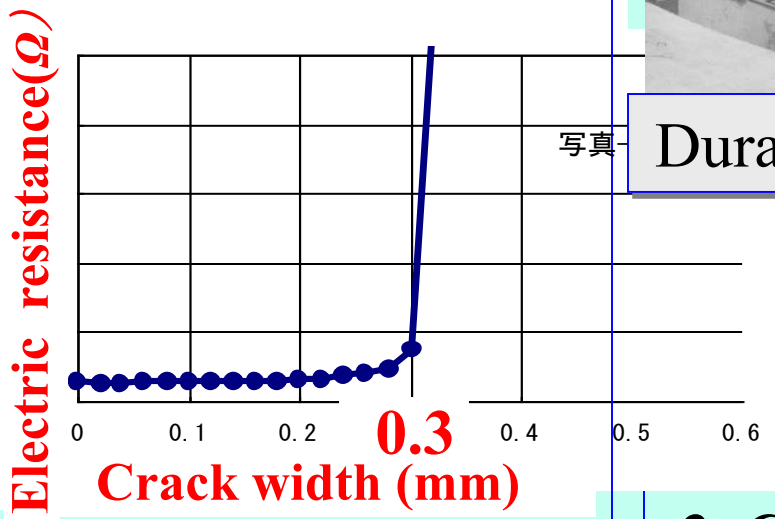
2 Accuracy of deformation occurring position
= ±20cm

2 Accuracy of strain =± 50-100μm
crack width = 0.3mm

Detection of cracks on lining with electric conductible paint (RTRI et al.)







Durability test

Model Test

...rits of the method

...imple and precise detection.

...ust in time monitoring.

3. Cost effectiveness.

5 Diagnosis of soundness

Diagnosis

- Judgement of soundness,
- Estimation of deformation course
- Planning of measurement

Increase of deformed tunnels

Decrease of skilled engineers

⇒ Development of automatic inspection methods

- ◆ **Expert system for tunnel diagnosis**
- ◆ **Manuals for maintenance work**

Judgment of Structure States and Standard Soundness

■For Structural performance

出典:鉄道構造物等　維持管理標準

Soundness		Structure State
A		State that threatens operational safety, safety of passengers, public safety, guarantee of regular train operation that might cause this state
	AA	Deterioration that threatens operational safety, safety of passengers, public safety, or the guarantee of regular train operation , and which require emergency countermeasures
	A1	Progressive deterioration that causes the performance of structures to drop, or heavy rain, floods, or earthquakes that might impair the performance of structure
	A2	Deterioration that might cause a future performance drop of structures
B		Deterioration that might result in a future soundness rank of A
C		Slight deterioration
S		Sound

Note: Soundness ranks A1 and A2, and soundness B, C and S may be categorized by individual railway operation in consideration of the actual inspection circumstances.

■ For Spalling

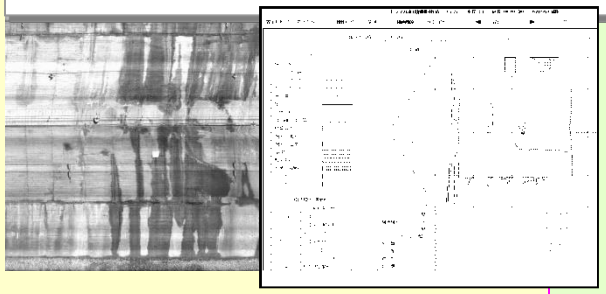
Soundness	Structure State
α	There is some possibility of spalling that threatens safety in near future.
β	There is few possibility of spalling that threatens safety for the moment. But, There is some possibility of spalling that might result in a future soundness rank of α.
γ	There is few possibility of spalling that threatens safety .

Expert system for tunnel diagnosis

Under study on the basis of existing system ***TIMES-1*** *(RTRI,1989)*

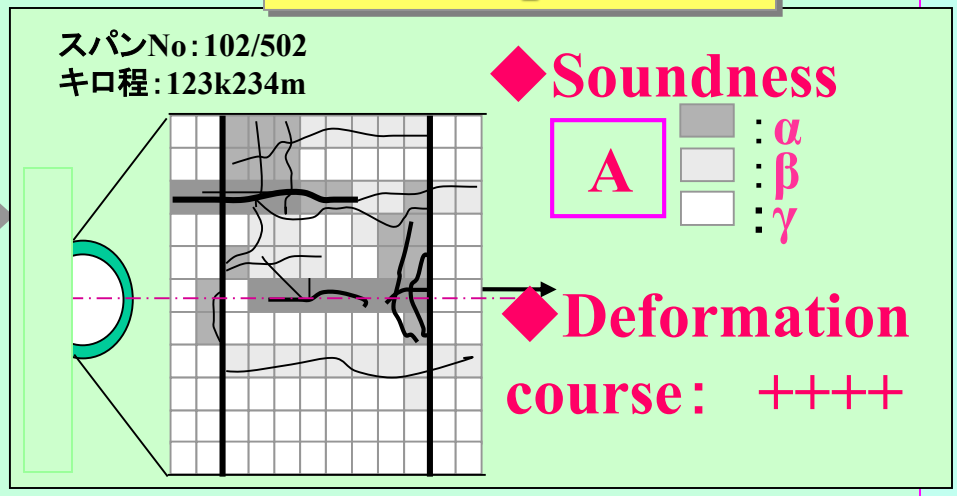
Input

- **Inspection data** *(primary, secondary)*
- **Tunnel structure**
- **Geography, geology**
- **History of countermeasures**



Diagnosis logic

Output



Maintenance Standards

・Maintenance Standards for Railway Structures and Commentary (Tunnel) (2007,RTRI, MLIT)

Manuals

Repair

・Manual for repair work of tunnels (2000, RTRI)

Adjacent construction

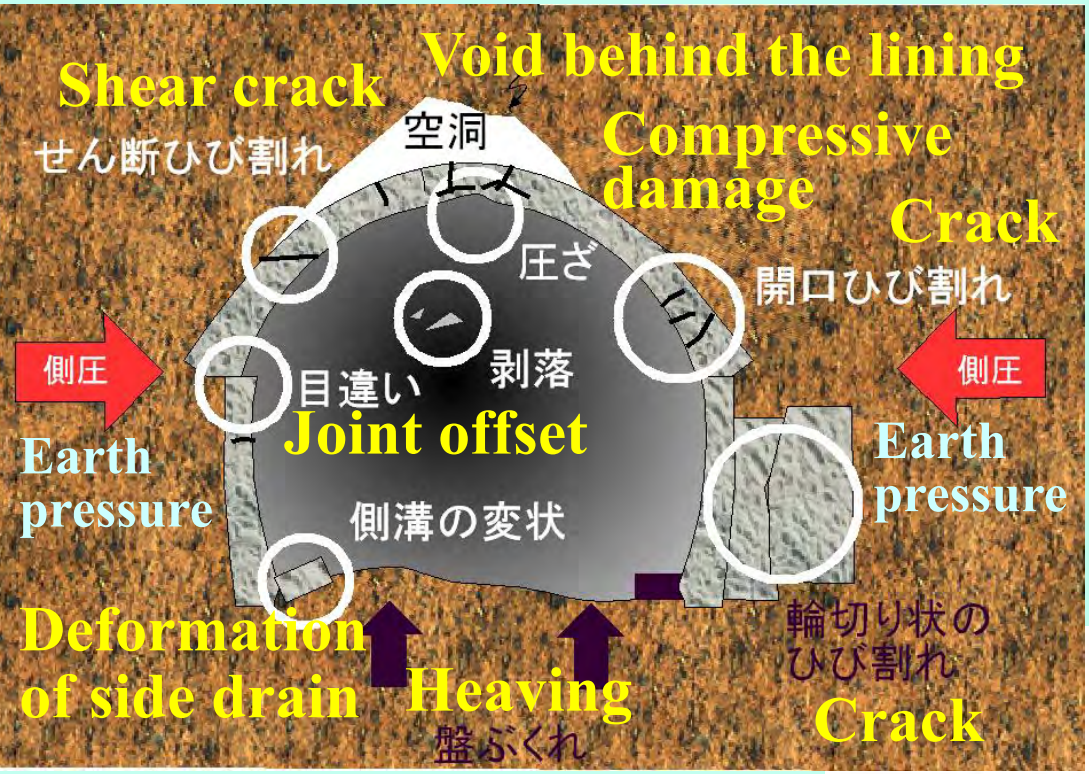
・Manual of countermeasures for construction near exiting tunnels (1995,RTRI)

Earth pressure

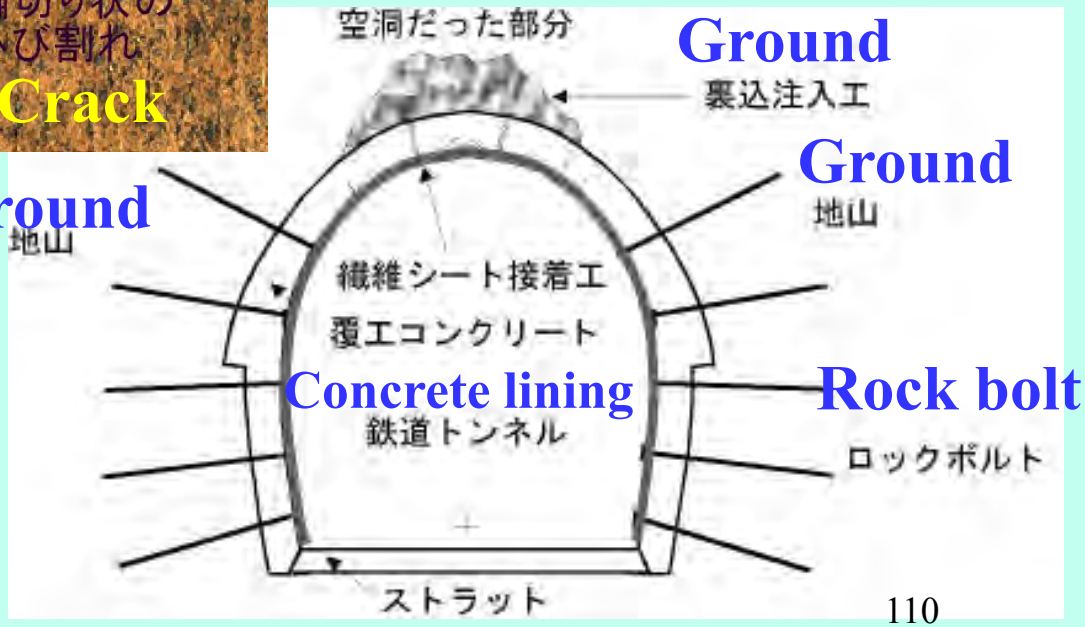
・ Manual of Designing method of countermeasures against deformed tunnels (1998, RTRI)

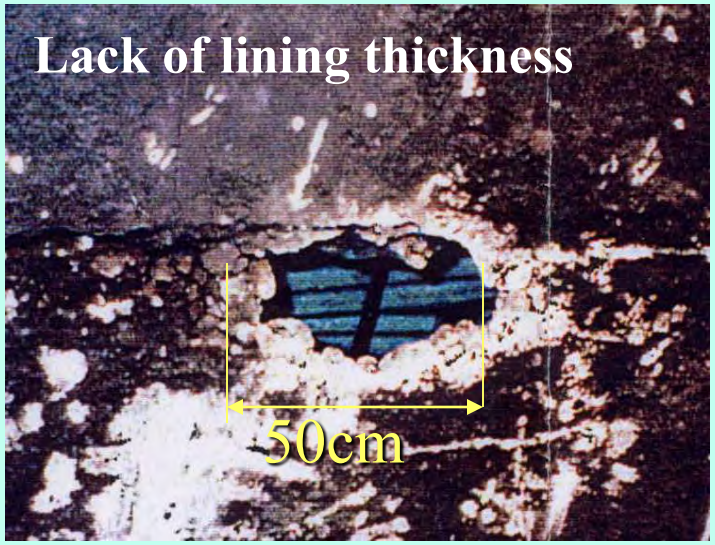
6 Countermeasures

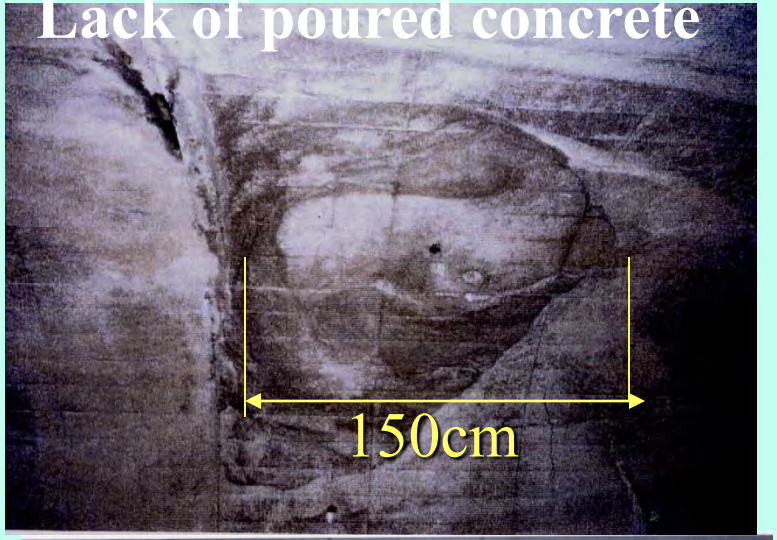
Example of deformation by earth pressure

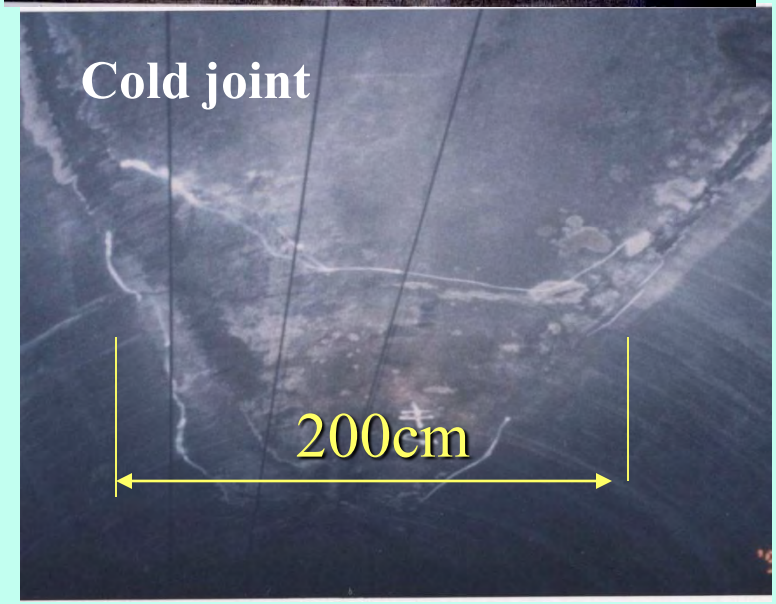


Example of countermeasure for deformation by earth pressure



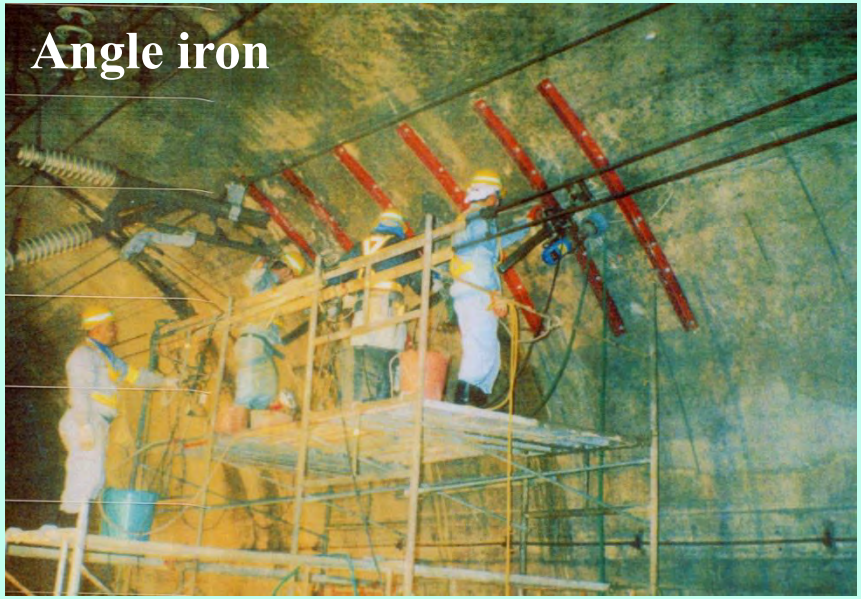


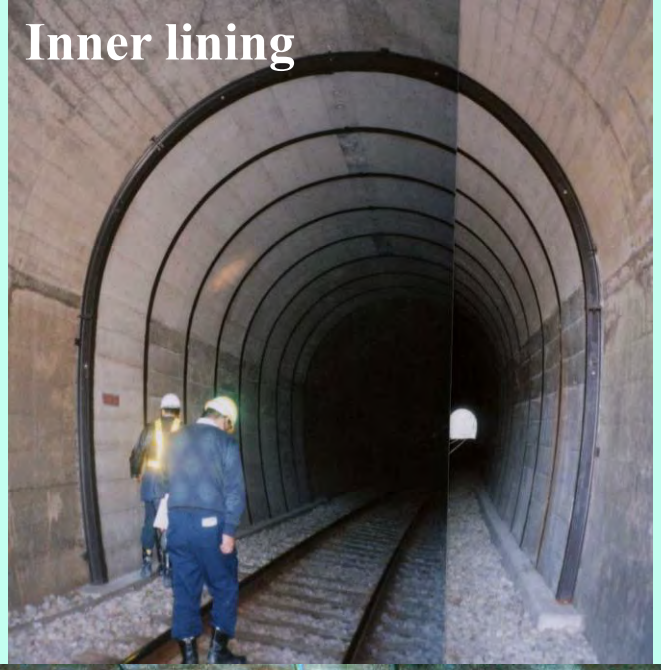


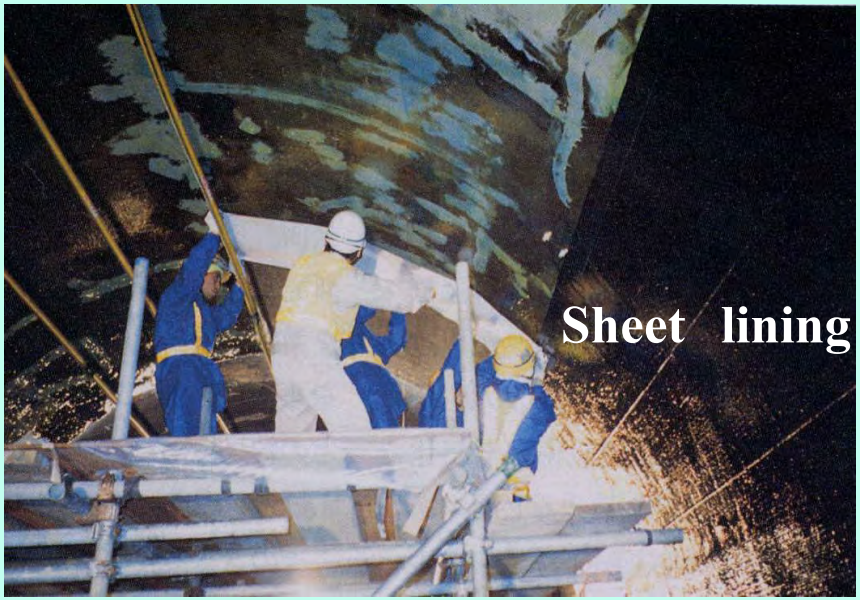


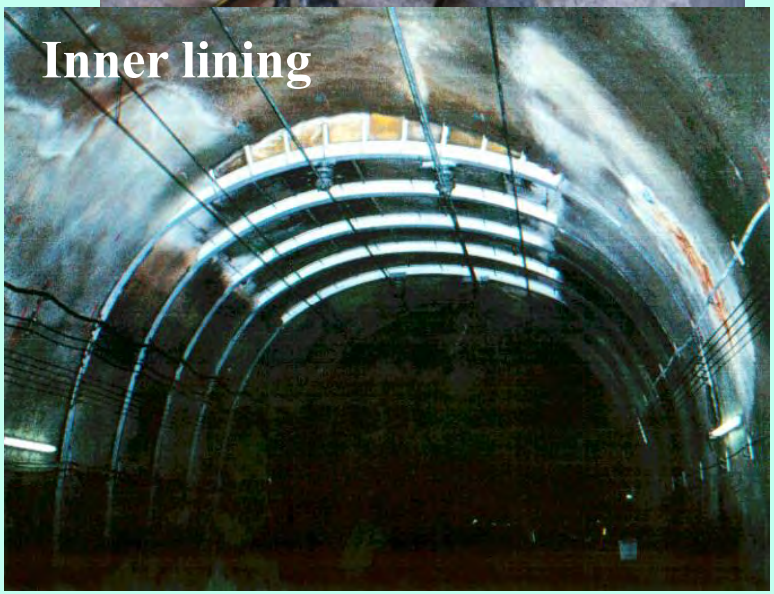
Examples of falling off or spalling

Structure defects, deterioration at construction





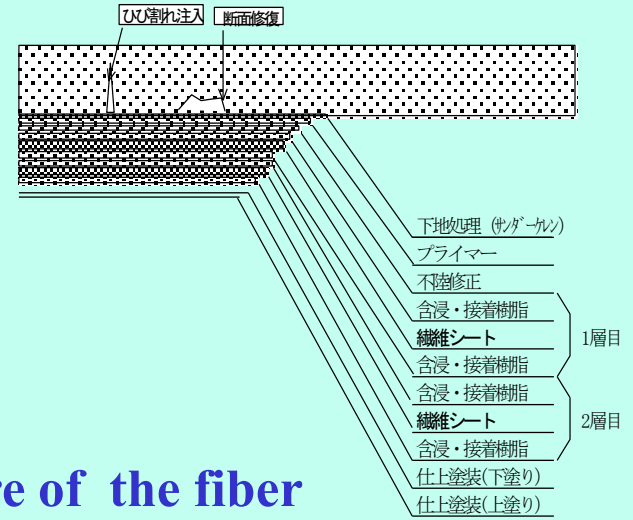




All sorts of fall-preventing methods

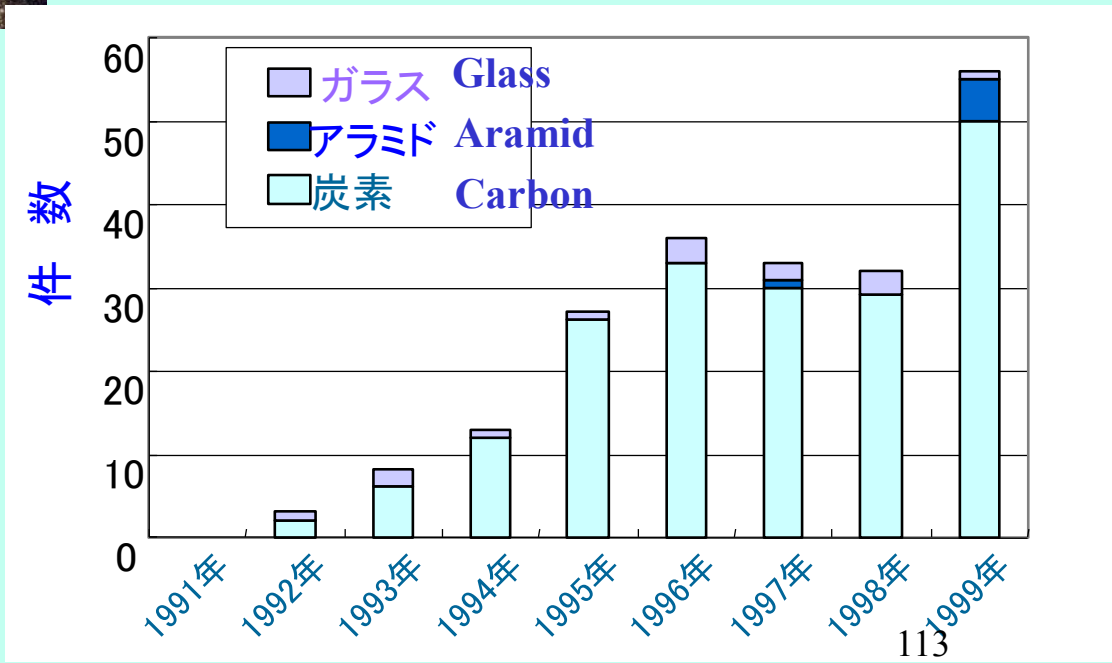
Fiber sheet lining method

An example：an application of carbon fiber sheet lining method



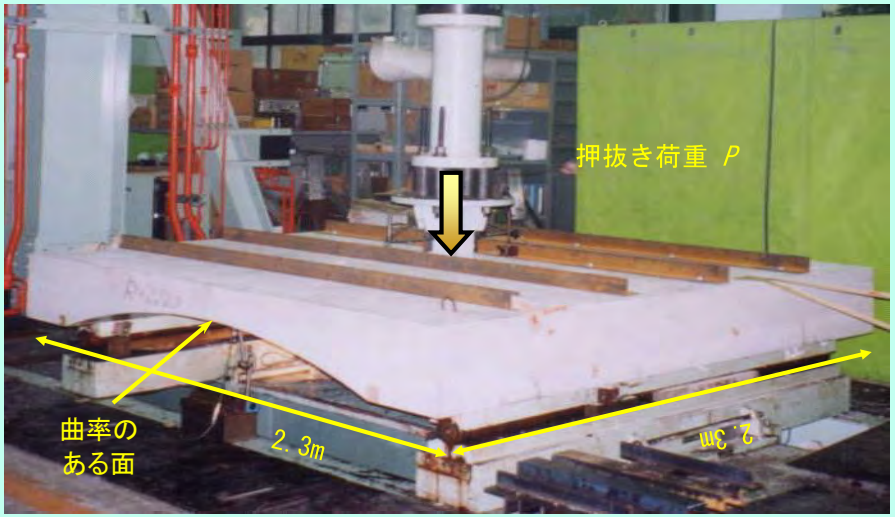
Structure of the fiber sheet lining method

Results of the fiber sheet lining method

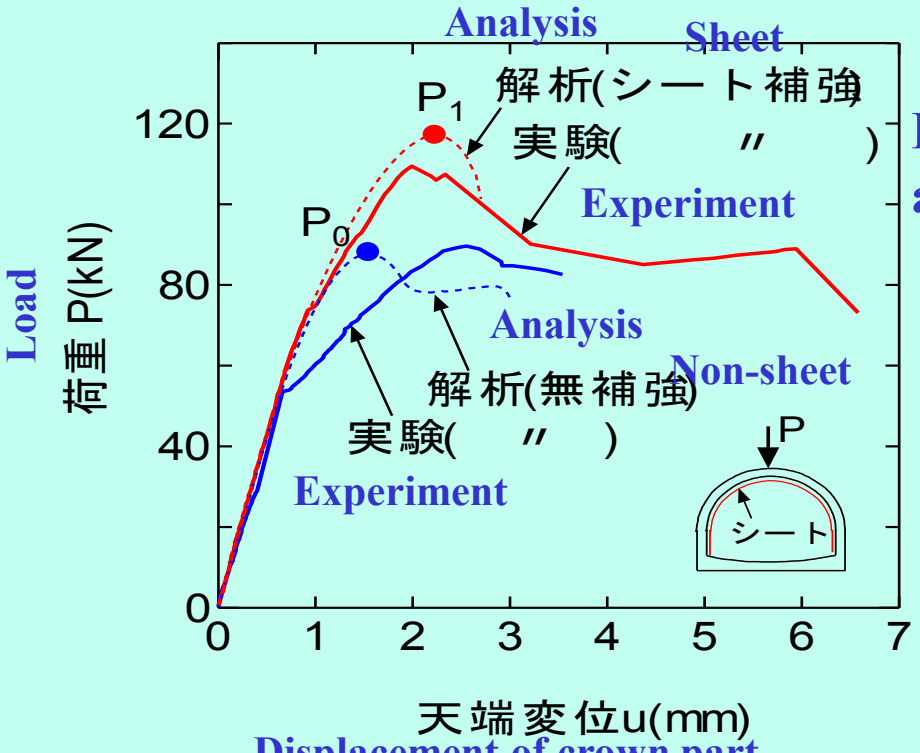


Simulation of experimentations

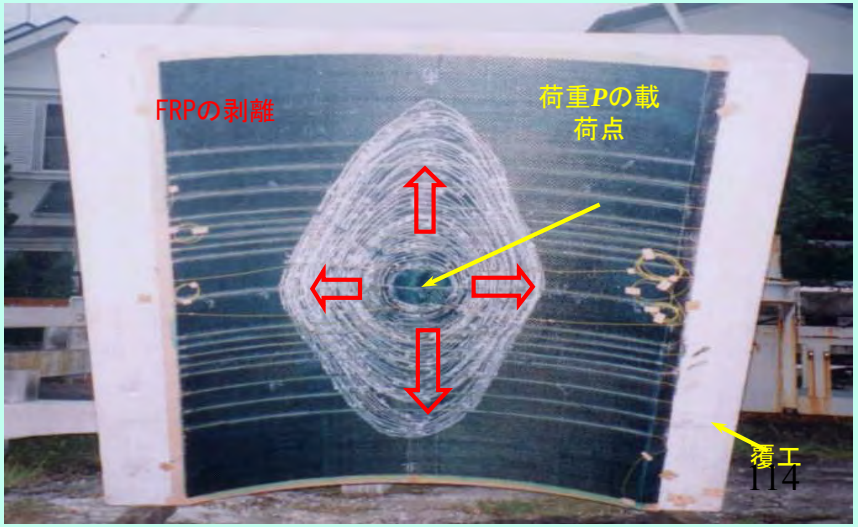
Punch experiment



Result of loading tests



Exfoliation of FRP after test



Aramid fiber sheet

Provided by JR Hokkaido

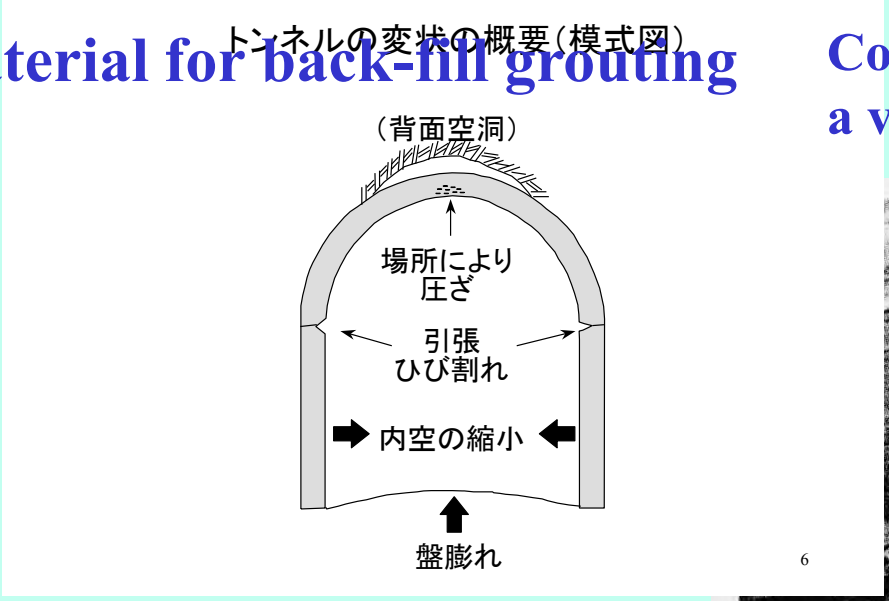
Transparent fiber sheet

Provided by JR East

Vinylon mesh sheet(Brick lining)

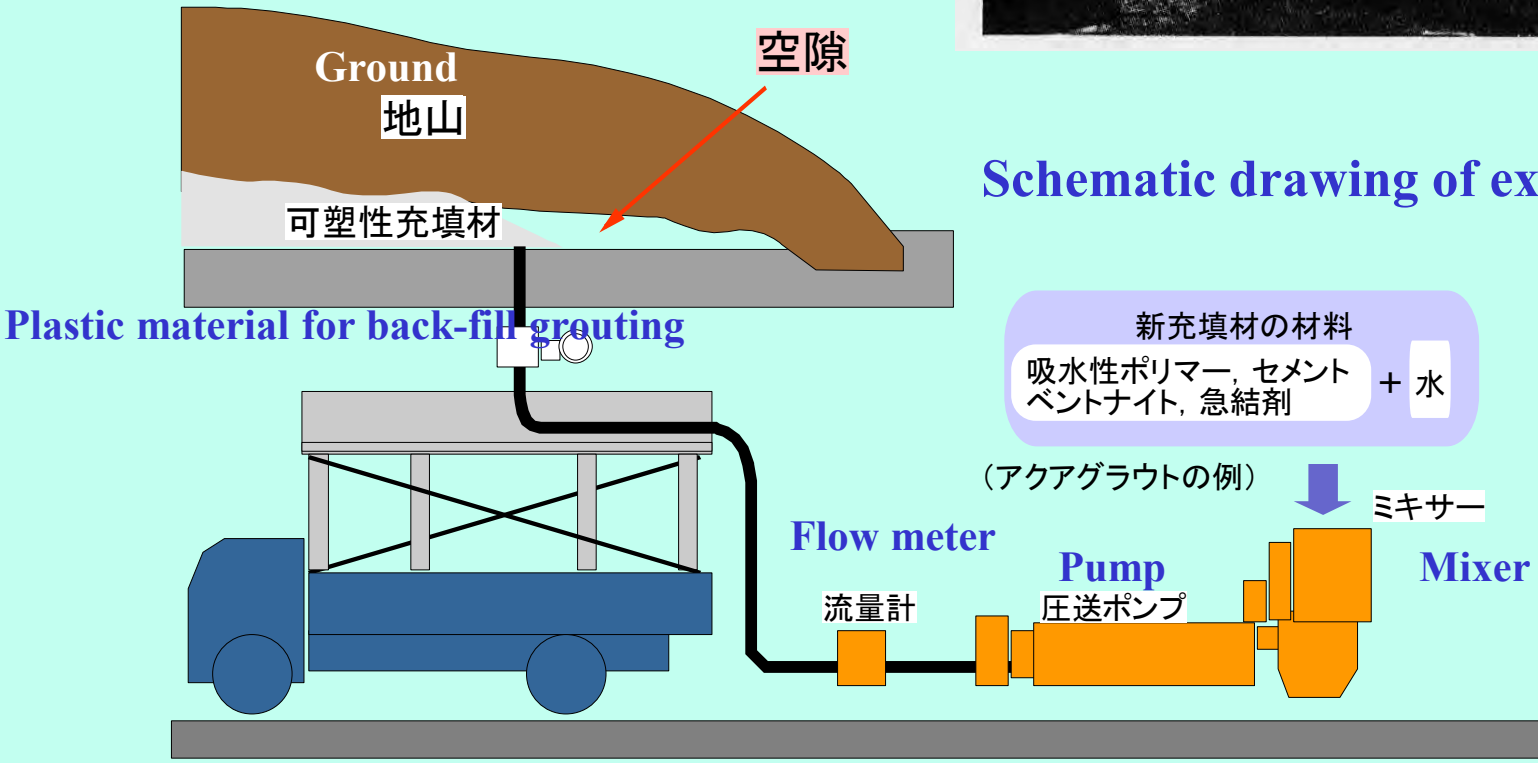
Provided by JRWest

Plastic material for back-fill grouting



Compressive damage due to a void behind the tunnel

Schematic drawing of execution



Plastic material for back-fill grouting

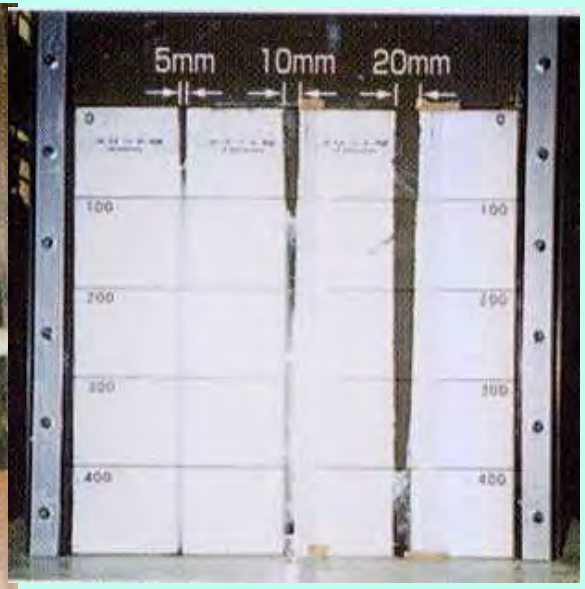
Absorbent polymer (Left: before absorption)

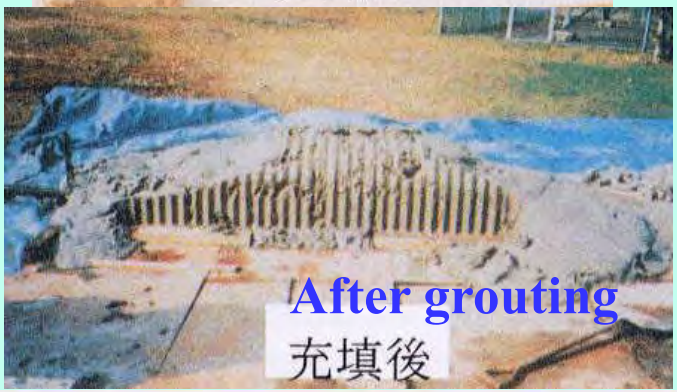
Test of material separation resistance in the water

Before giving vibration

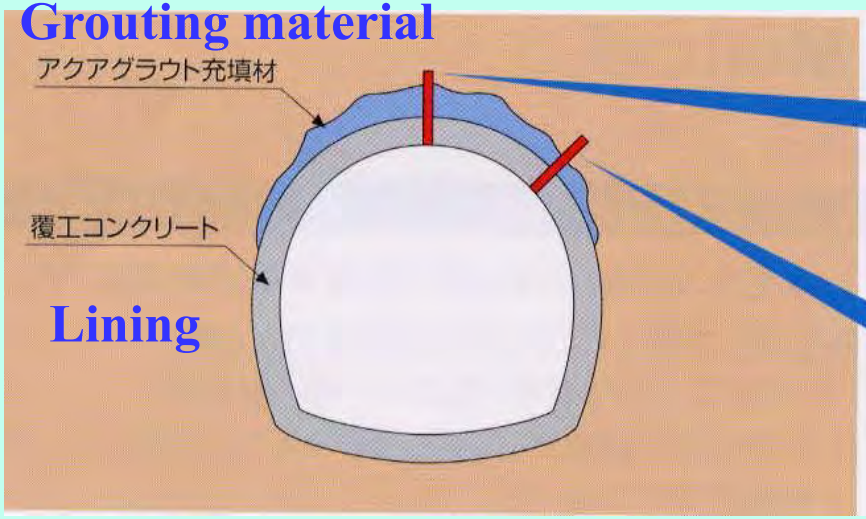
After giving vibration

Aqua-grout

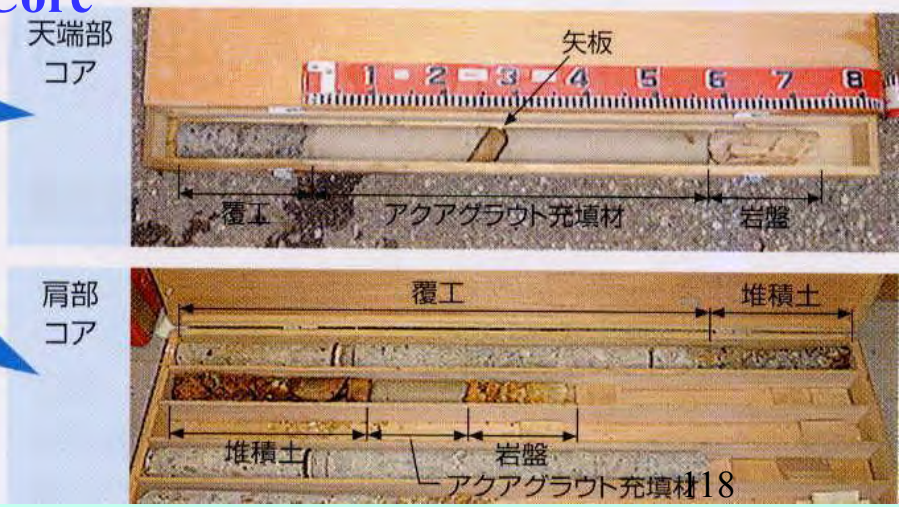




Grouting material



Core



Maintenance of shield tunnels.

Maintenance

For shield tunnels

Remake is significantly difficult. → **Maintenance is very important.**

High water pressure

Difficulty of access

} → **Reinforcement and repair are very difficult**

Desired technique

Backfill grouting under high water pressure

Prevention of leakage under high water pressure

Efficient internal reinforcement method

Estimation of degradation

Long-term measured data are need.

Examples The Soubu tunnel in Soub line

A use: Railway tunnel

Lining constitution: RC plane segment

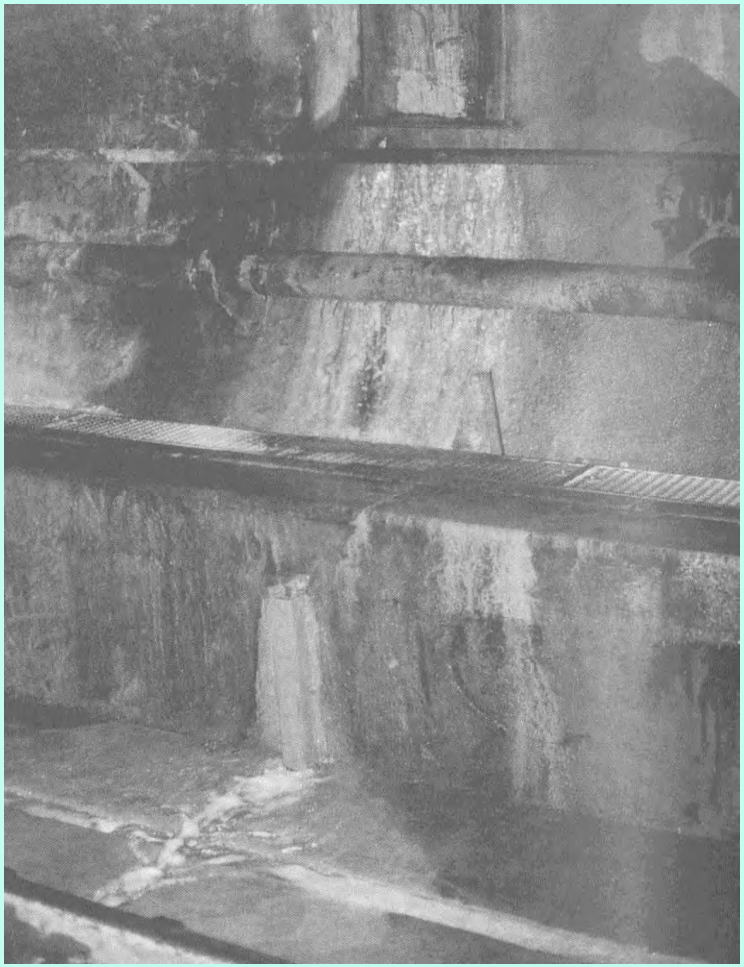
Length of execution: 9,500m(Tunnel)
5,500m(Execution)

Ground condition: Alluvial sandy ground

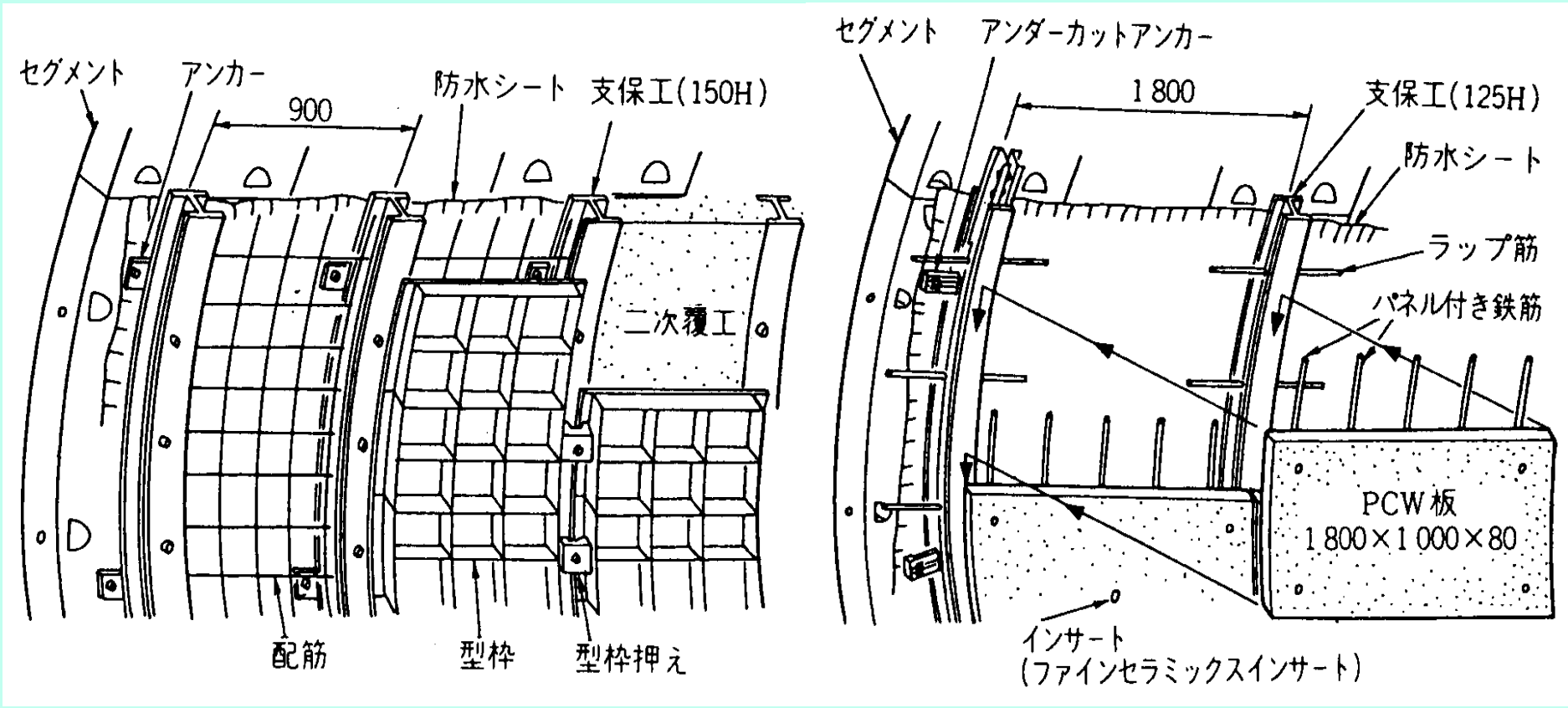
Under ground water level :
At design ---------- Below tunnel
After the regulation of pumping up – Above tunnel

Year of construction: 1976

Countermeasure: Secondary lining



Deformation and leakage of the tunnel



(a) Conventional method **(b) PCW method**

(Ply propylene reinforced concrete wall)

Schematic drawings of the secondary lining

Before setting PCW plates

Setting PCW plates

A finished product

Examples

Railway tunnel in Hong Kong

A use: Railway tunnel

Lining constitution: RC box type segment

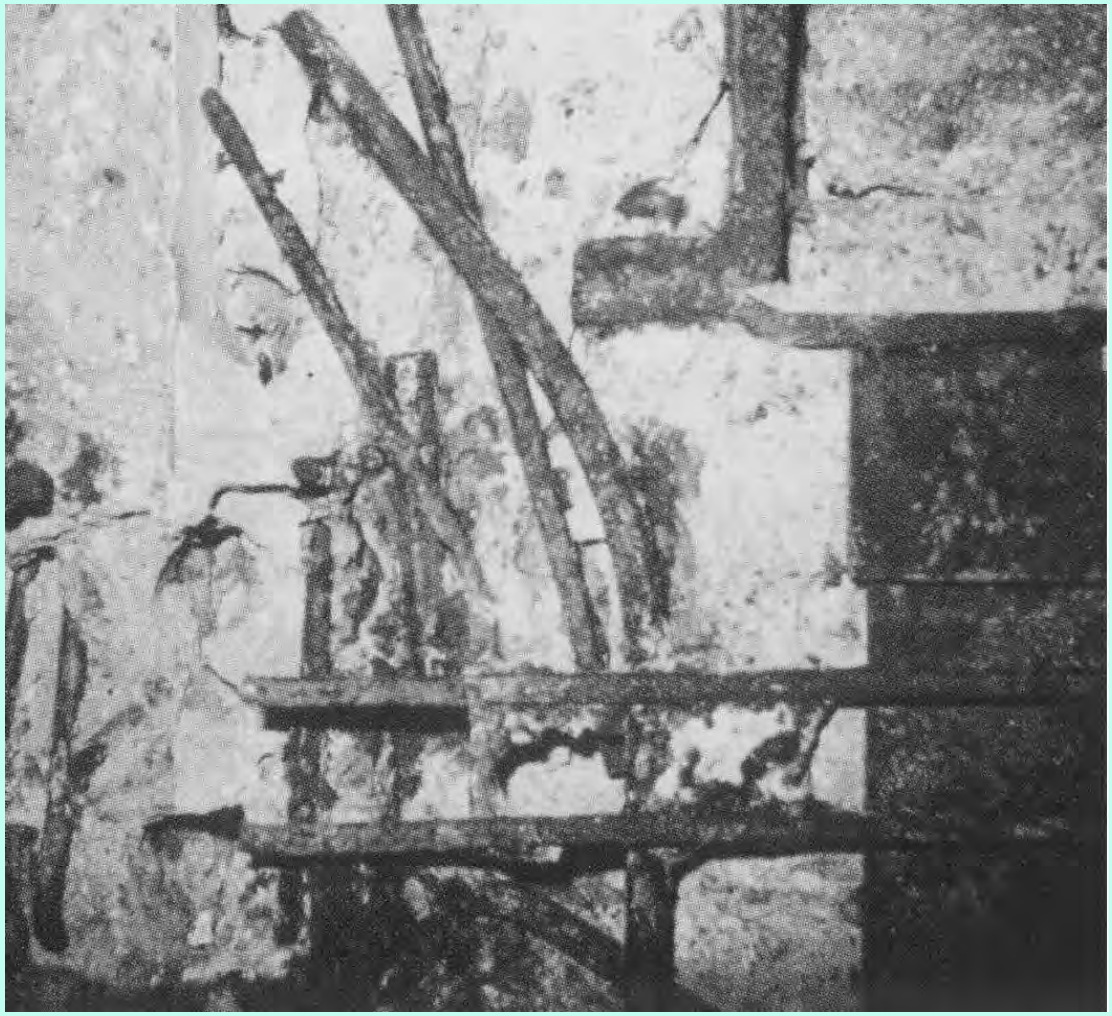
Length of execution: 40km(Execution)

Ground condition: Unknown

Under ground water level : Unknown

Year of construction: 1980

Countermeasure: Shotcrete concrete
(Thickness:75mm)



Corrosion due to ground water with salt

Examples Road tunnel in Egypt

A use: Road tunnel

Lining constitution: RC box type segment

Length of execution: 1,640m(Execution)

Ground condition: Mudstone

Under ground water level : -50m from the surface of the sea (the deepest part)

Year of construction: 1983

Countermeasure: Secondary lining

Degradation of segments and joints

A gap at the joint part of the segment

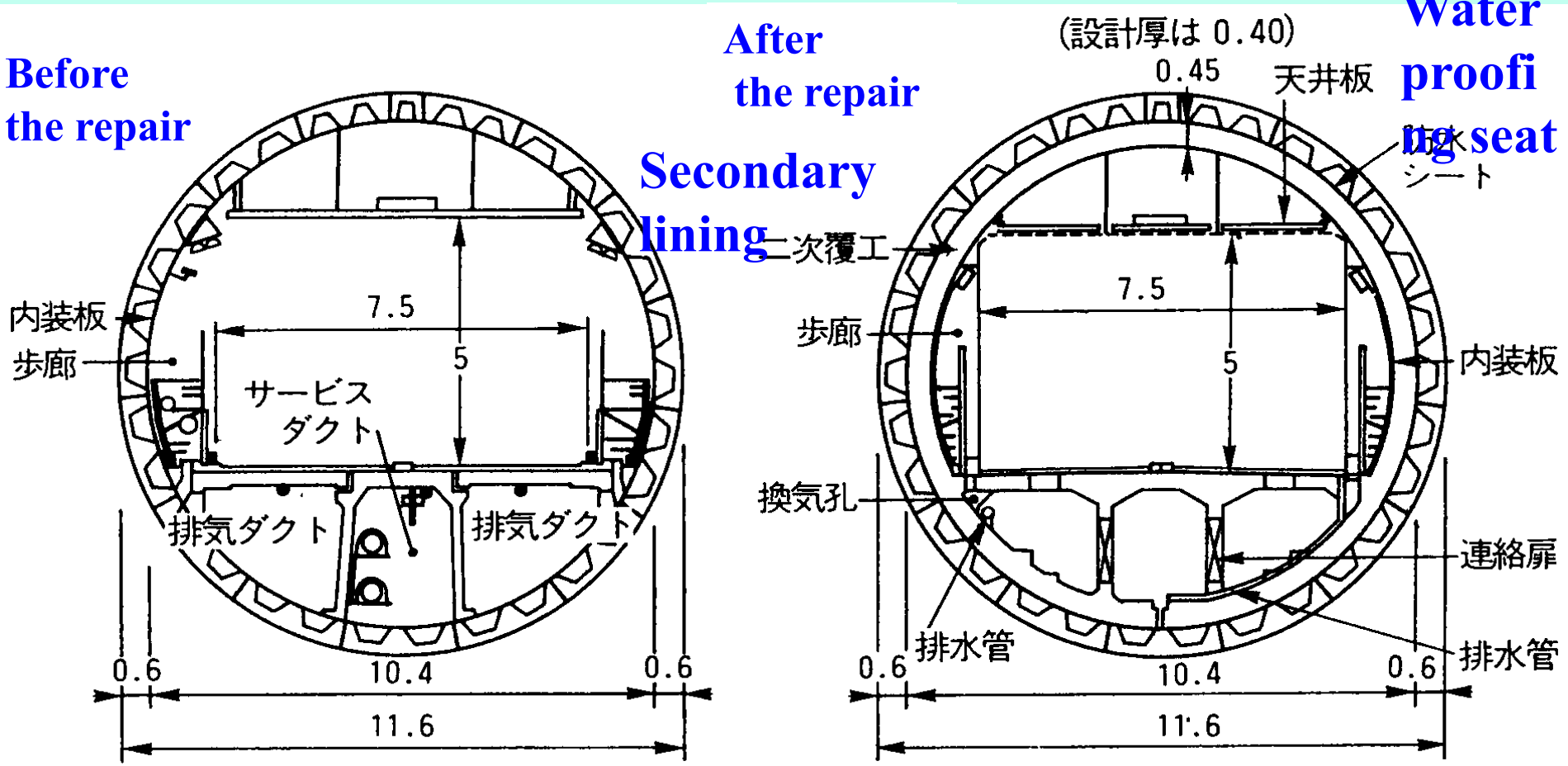
Corrosion of reinforcing bars in the slab

Before the repair

After the repair

Secondary lining

Water proofing seat



Linings before and after the repair

Assembling reinforcing bars of the secondary lining

7 Conclusion of My Lectures

My Advice for you!

My advice for engineer（on a construction site）

技術者へのアドバイス

>Feel strangeness at a glance. ➡ >Knowledge, Experience (look at various construction sites.)

○ パッと見て，どこかおかしいと感じる→知識，経験，いろいろな現場を見る

>Think ahead. ➡ >Predict possible troubles. ➡ >Avoid troubles. >Preparation for taking countermeasures to the troubles.

○ 先を読む→起こりうるトラブルを予測する→トラブル回避，起きた時の備え

>Simple is the best. ➡ >Complexness causes accidents.

○ シンプルが一番→複雑はトラブルのもの

My advice for engineer（on a construction site）

技術者へのアドバイス

>Time is money. ➡ >Decide quickly how to cope with a trouble when it happen.

>Buy time.
>After that, modified the countermeasure with observing the situation.

(If the possibility that a countermeasure will succeed is over 50%, you have to go ahead.)

○ 時間が勝負→対処方法を早く決めて，時間を稼ぐ。その後，様子を見ながら対処方法を修正する。

Imagination is very important. ➡ >Image what's happen and how does it happen in the blind spaces.

○ イマジネーションが大切。→見えないところで何が起きているかイメージ

My advice for young researcher
若い研究者へのアドバイス

> **Have a sense of your time!** **(the future plan, a day, a week, a month, a year, a decade, a life)**

○ 時間軸を持とう！ （日，月，年，3年，10年，人生）

> **Have pleasure in your research!** **(Device, Originality)**

○ 研究の中に楽しみを持とう！ （工夫，オリジナリティ）

> **Make a core of your knowledge!** **(Snowman)**

○ 知識の核となる部分を作ろう！ （雪だるま）

My advice for young researcher
若い研究者へのアドバイス

> Value your communication! (In the university, Outside the university)

○ コミュニケーションを大切にしよう！ （学内，学外）

> Put yourself in a the other person's place!

○ 相手の立場になって考えてみよう！

> Take care of your health!

○ 心身の健康に気をつけよう！