NATM

May 26th 2016 Lecture at Waseda Univ.

Shinji KONISHI

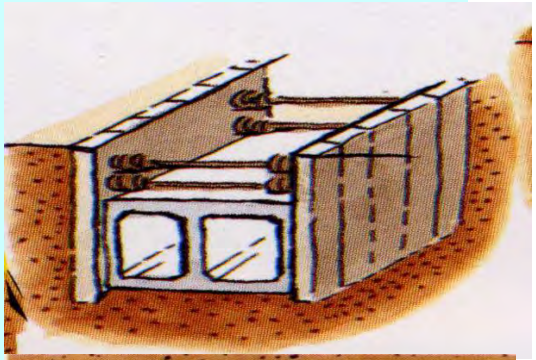
Types of Tunnel & Construction Methods

What's Tunnel?

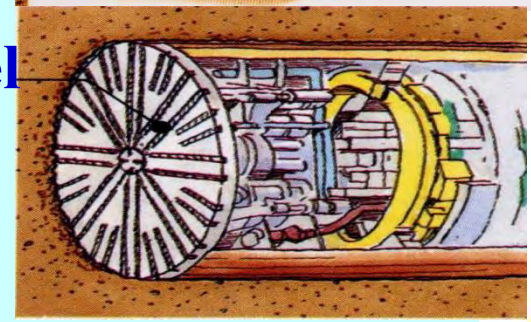
What's a tunnel made of ?

Types of Tunnel

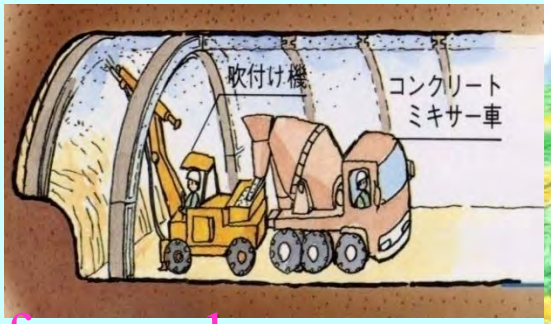
Cut & Cover Tunnel



Shield Tunnel



Mountain Tunnel



Difference of ground

Difference of construction method

Excavation of top heading

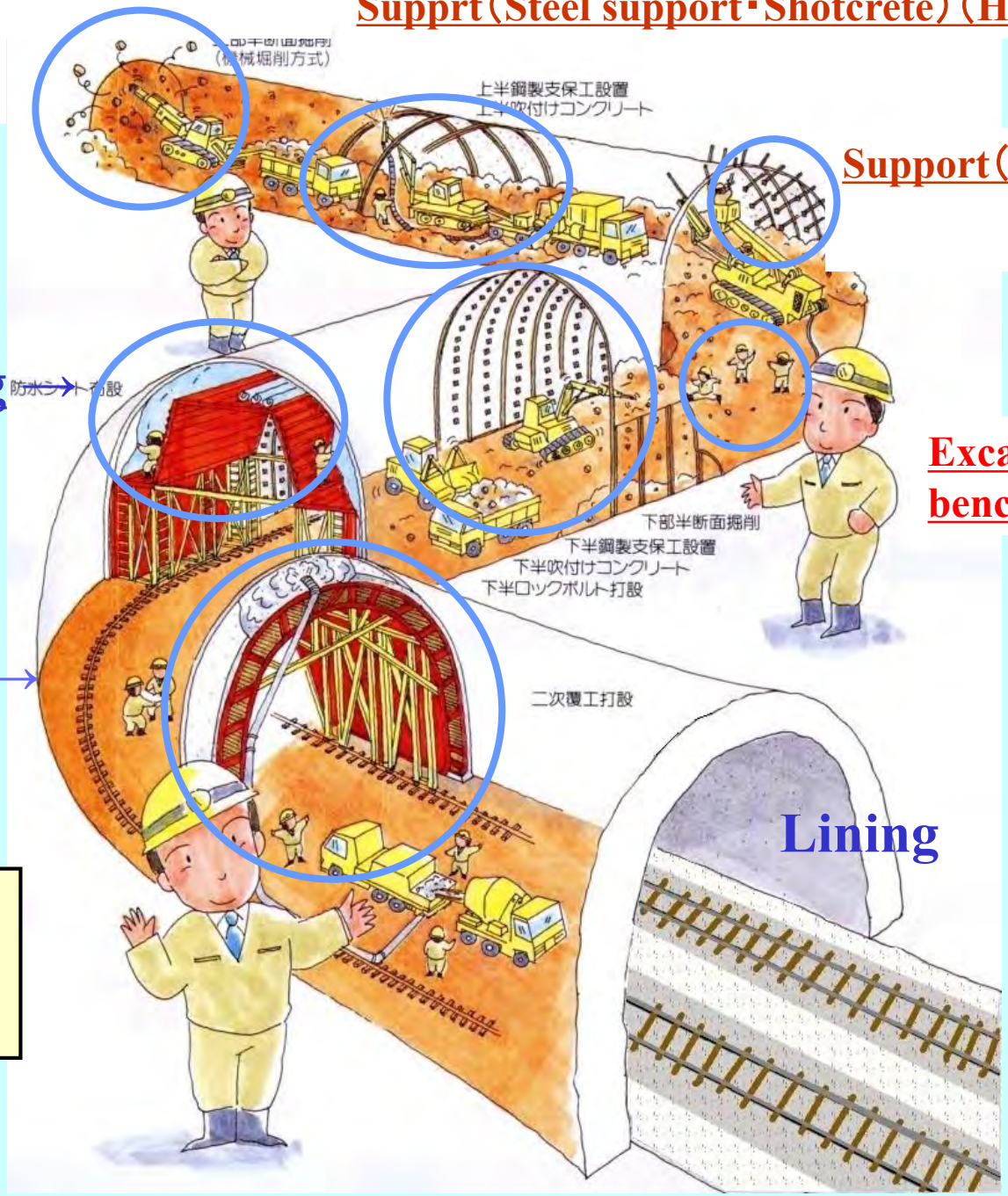
Supprt（Steel support・Shotcrete）（Heading）

Support（Rock Bolt）（Heading）

Water proofing

Excavation of bench

Placement of Lining Concrete



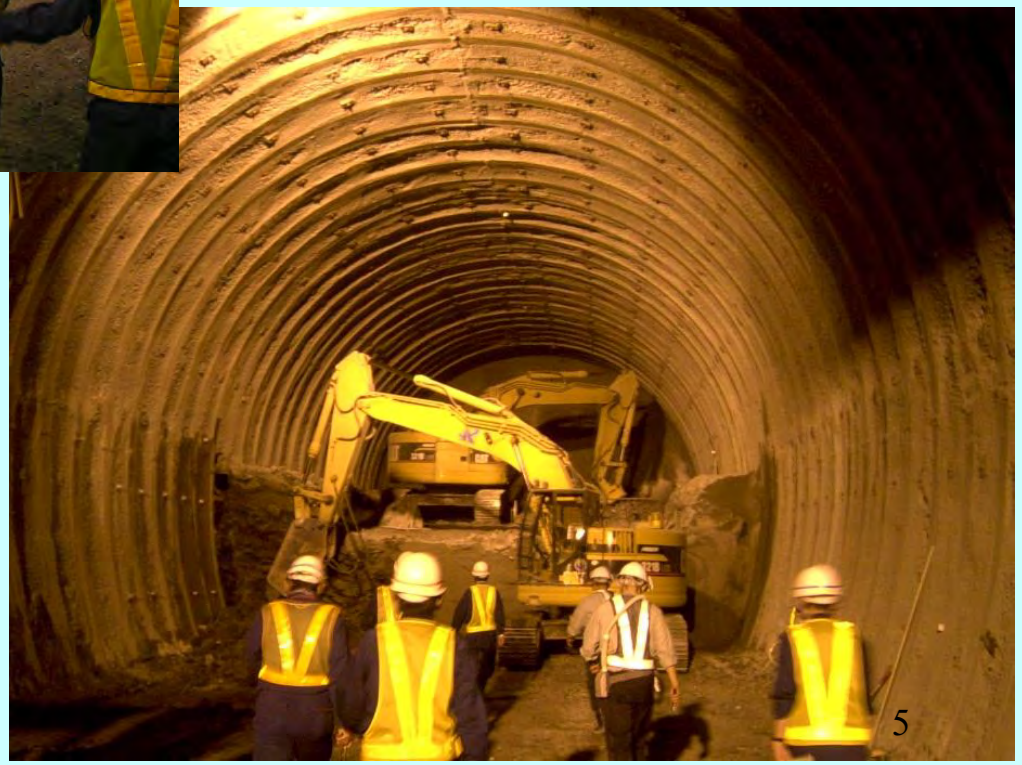
Lining

Process of constructing tunnel by NATM

MOUNTAIN TUNNEL

Mucking

Excavation
（Road Heading Machine）



MOUNTAIN TUNNEL

Erecting Steel Supports Setting and Grouting of Rock Bolt

MOUNTAIN TUNNEL

Shoot Shotcrete（Shotcrete）

MOUNTAIN TUNNEL

Hakkouda tunnel

Railway tunnel

Traveling stage for setting water proof seat

Water proof seat

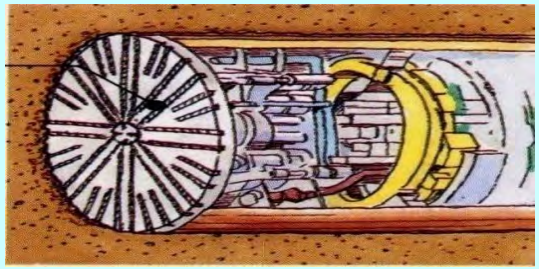
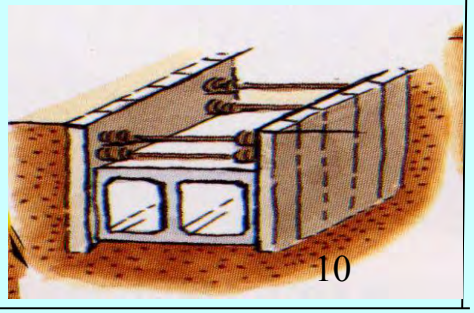
Traveling form

MOUNTAIN TUNNEL

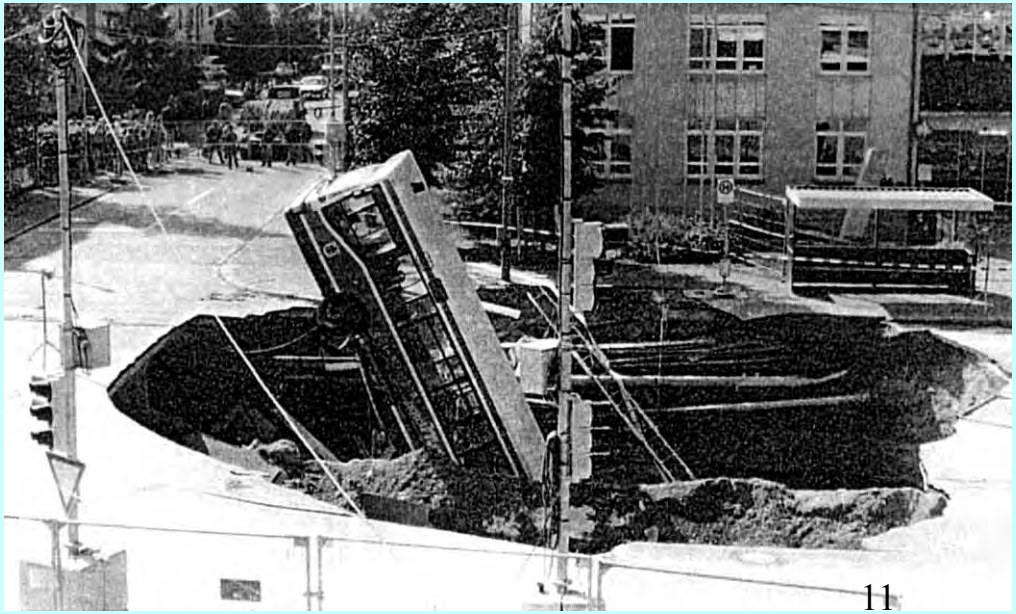
Concrete placement

坑外基地

COMPARISON-1.Outline of construction methods

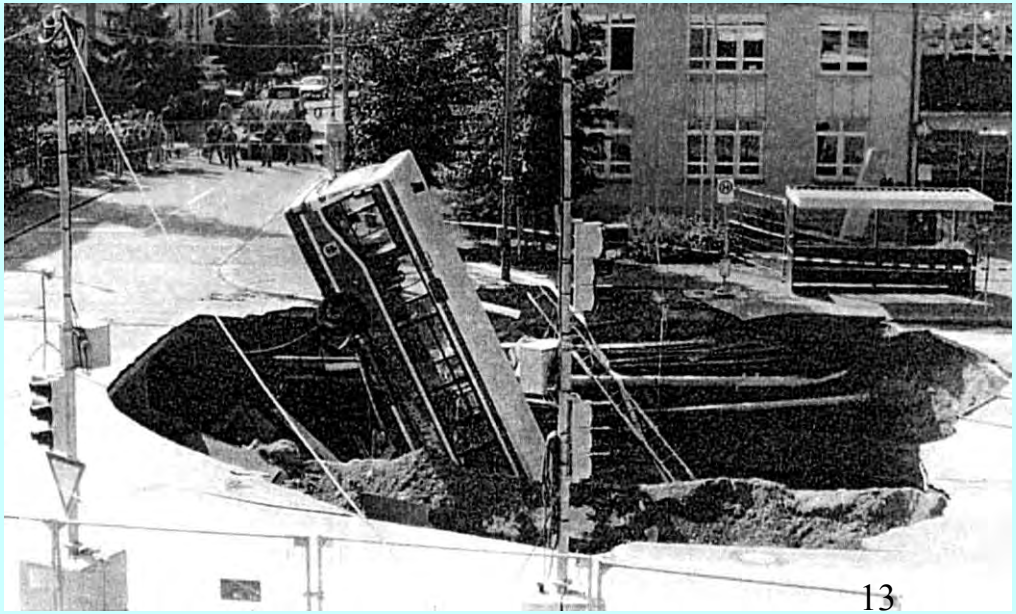
NATM	Shield	Cut & cover
▪ **Shot Crete, Steel support, Rock Bolt**	▪ **Segmental Lining.**	▪ **Earth-retaining wall, Main body**
▪ **Making full use of the natural support function of the surrounding ground**	▪ **The skin plate of the shield machine, outer backfill layer of the shield and the segmental support the wall of the tunnel.**	▪ **The ground excavated from the surface to build the tunnel at the desired depth. Then the excavated earth is brought back to restore the surface.**
▪ **Prerequisite condition is that face remains standing when excavated**	▪ **Closed-type shield stabilizes the face using earth or slurry to counter earth or hydraulic pressure.**	
		

Face collapse



Face collapse

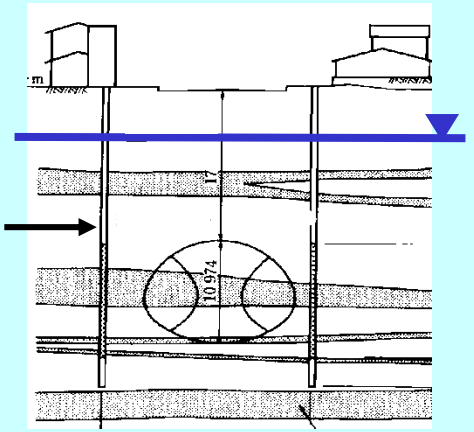
Face collapse



COMPARISON-2.Countermeasure for underground water

NATM	Shield	Cut & cover
▪ When there is water inflow that affects the self-support of the face or stability of the ground during excavation, water sealing method such as by deep well, well point, or drainage tunnel is necessary.	▪ Usually, closed type shield does not required countermeasures, but the open type does.	▪ Countermeasures such as deeper penetration of earth retaining wall, groundwater reducing method, soil improvement etc. are usually necessary to overcome boiling or heaving.

Deep well.



Natural water level.

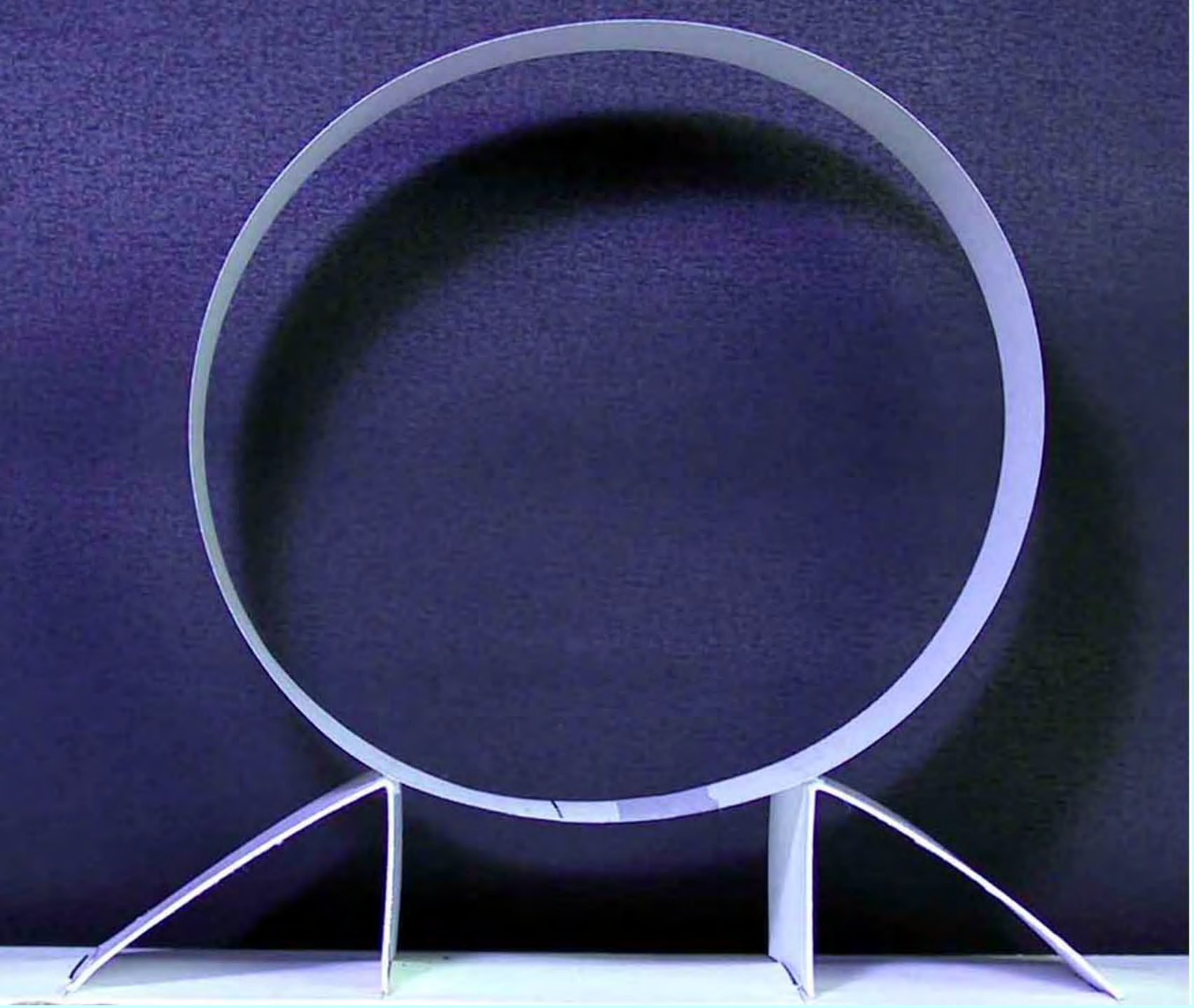
Railway Tunnel
NATM

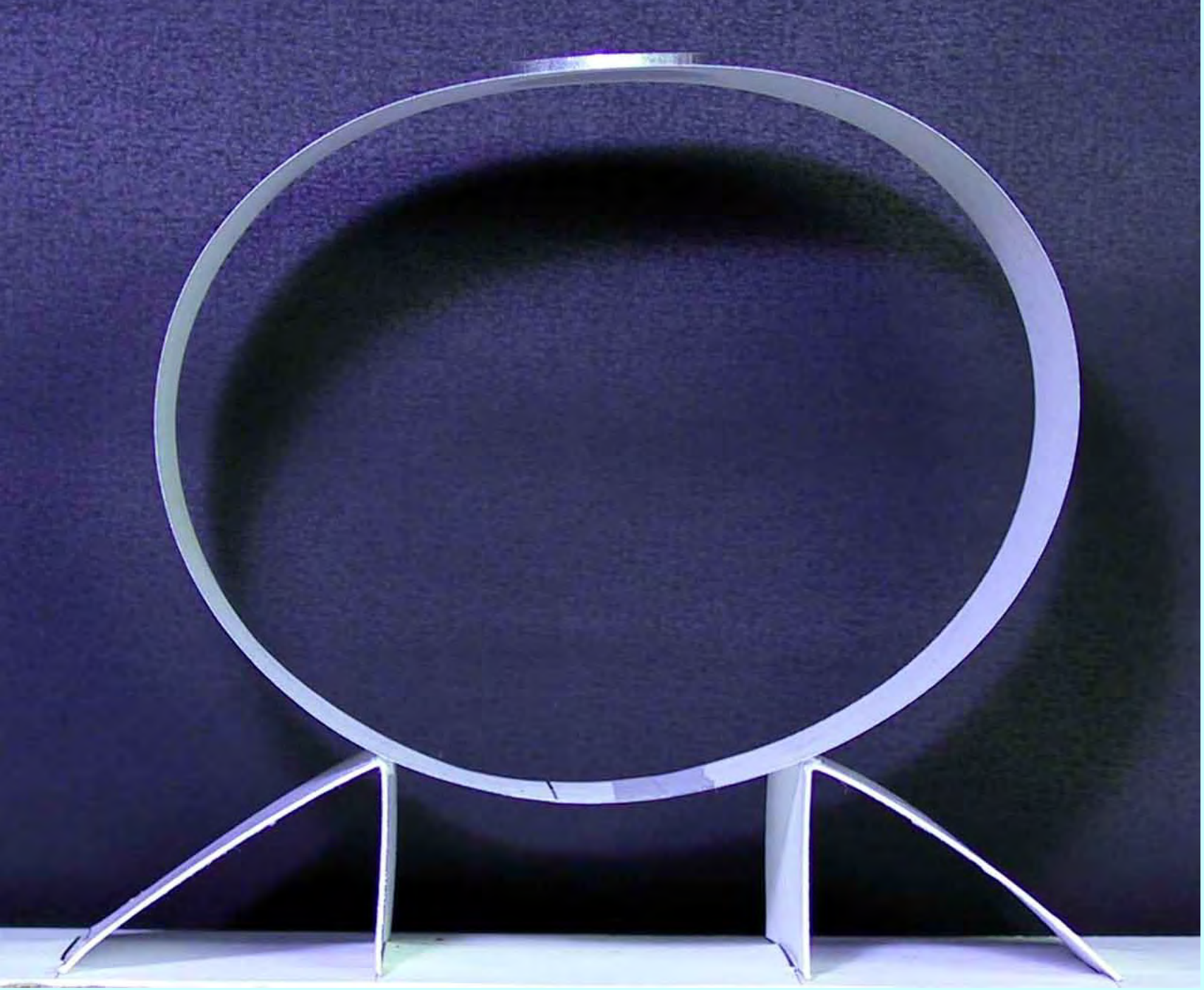
Portal Hood for reducing
tunnel compression wave

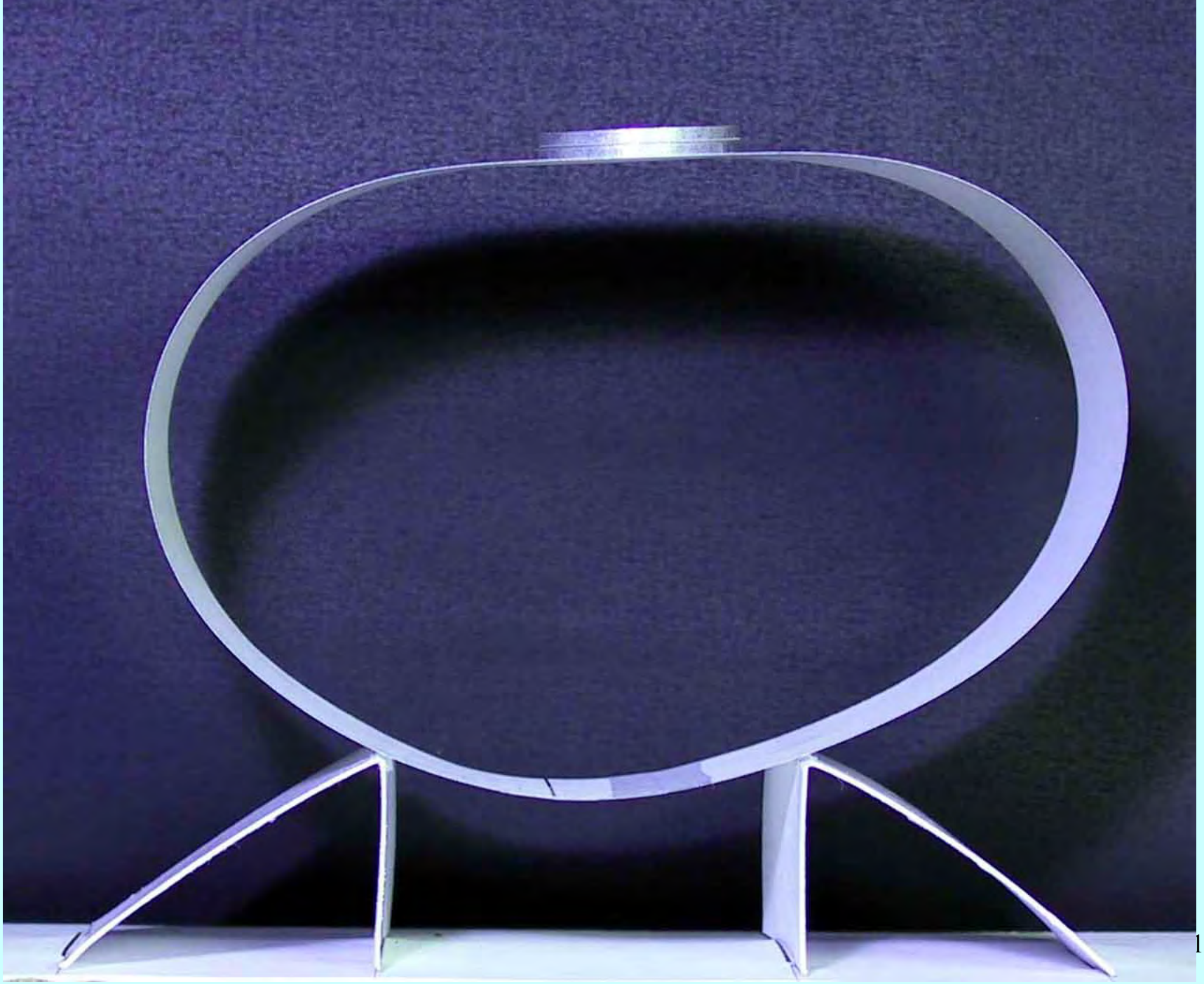
For Shinkannsen Double Track Tunnel

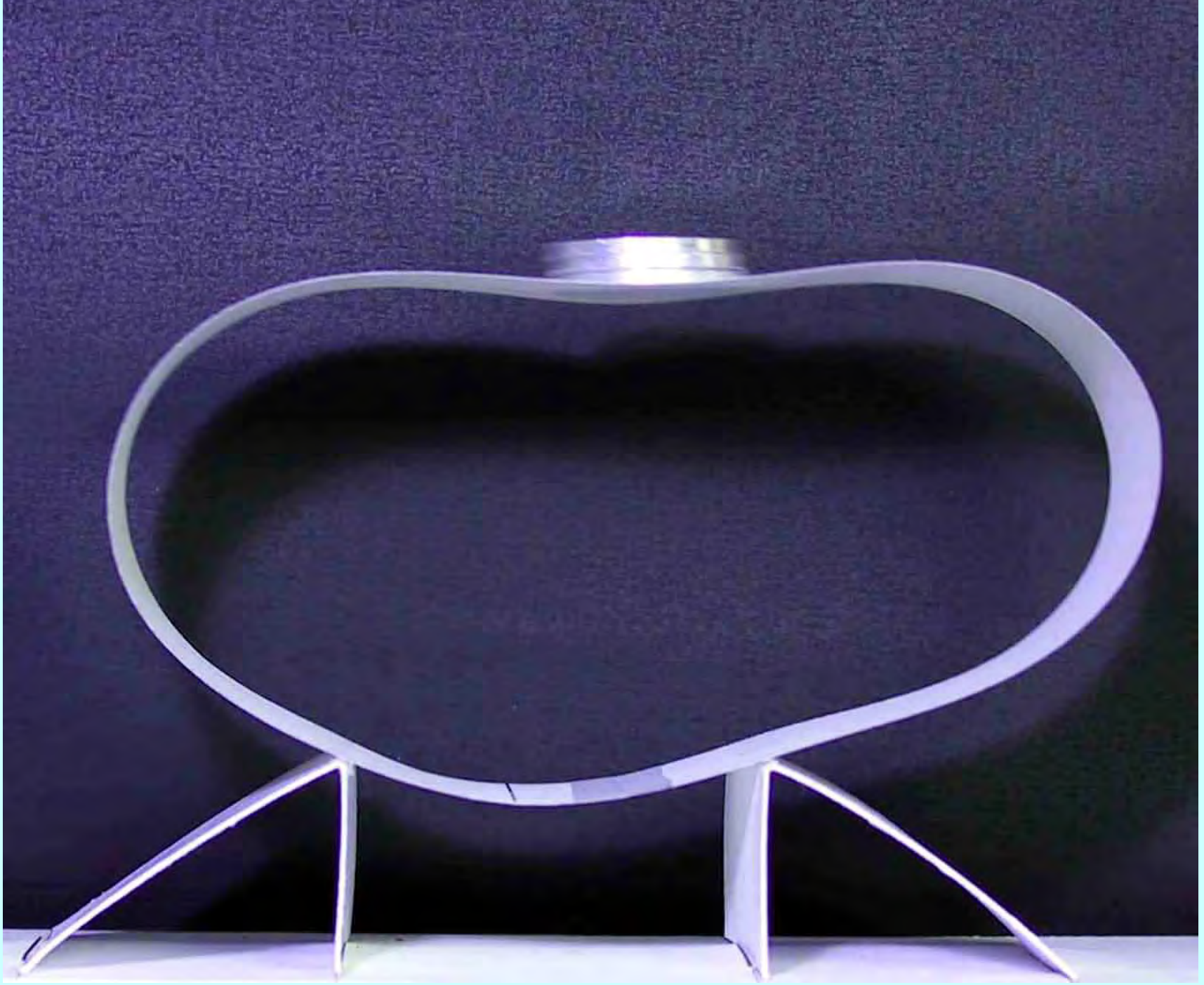
What's Tunnel?

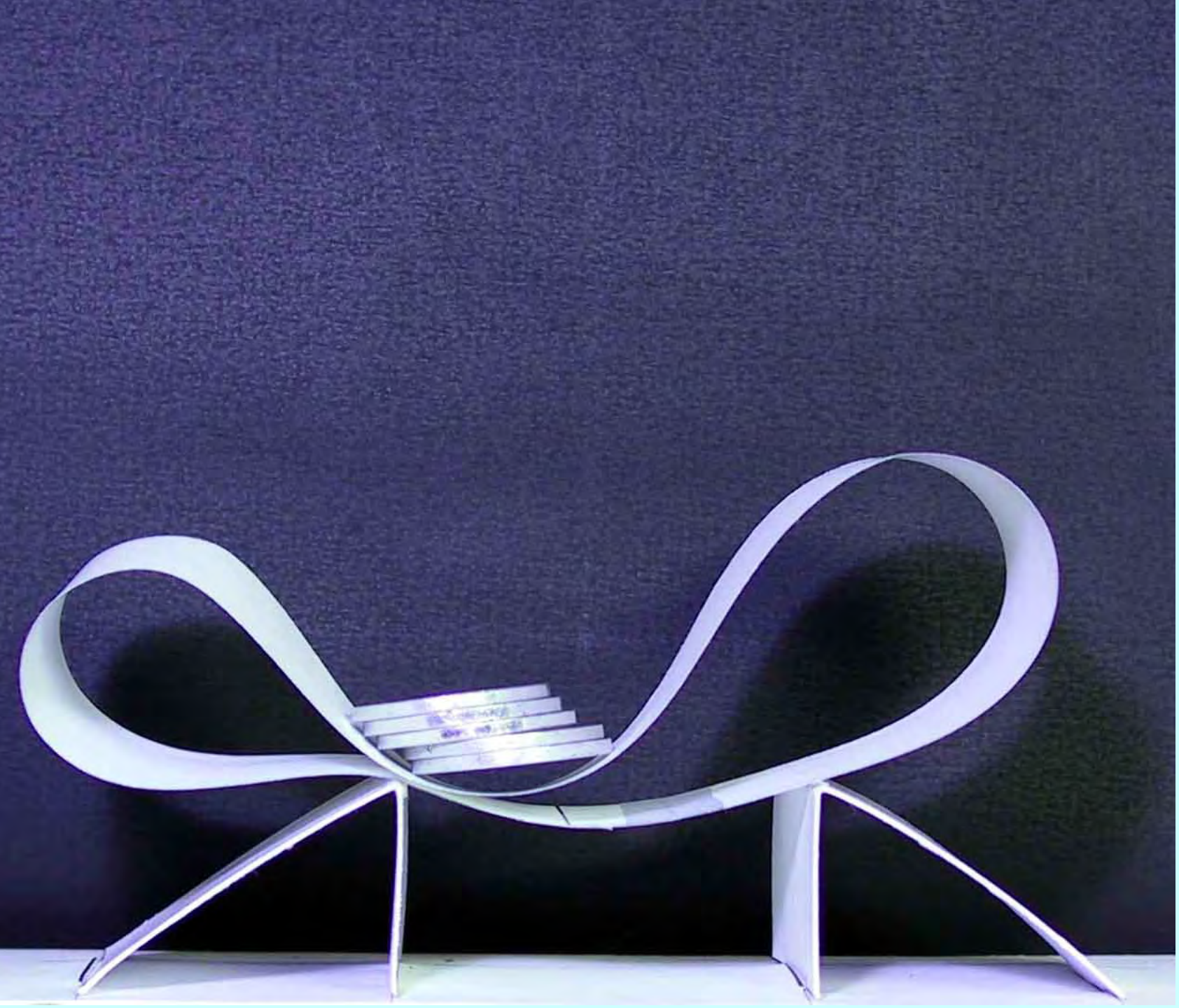
What's a tunnel made of ?











Peck's theory (to NATM)

Characteristic of flexible structure with thin-walled closed cross section

* Through deform for itself, tunnel shifts to stable state.

* Tunnel requires support from surrounding ground.

= **a Principle of Tunnel**

Deform according to the deformation of ground!

Railway tunnel

（Ooigawa Railway Line）

Mountain tunnel
Timbering support method
Block structural lining

After Chuetsu earthquake

Wanatsu tunnel

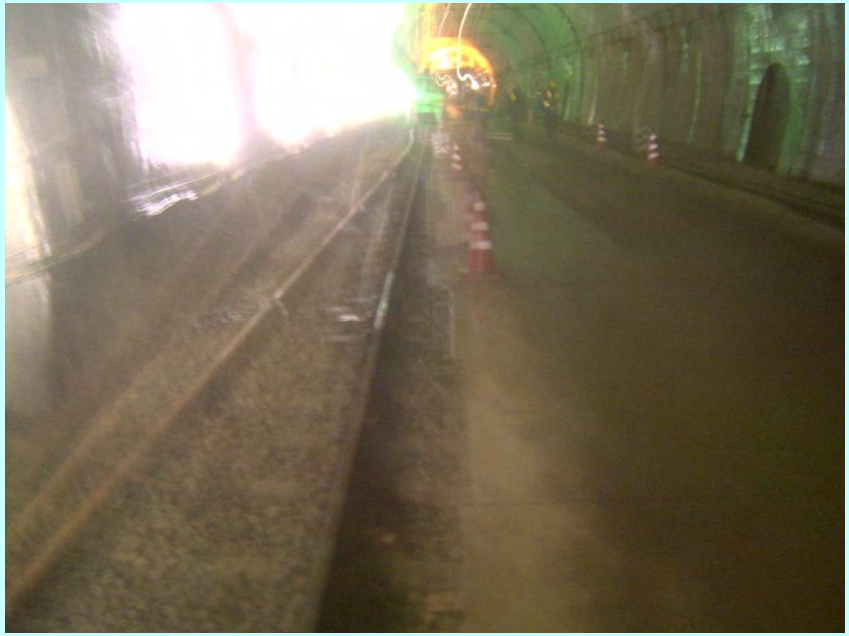
Near portal construction

The rail track was deformed.

The electric railway cable and pole were deformed.

Many slopes slide.

Portal gate moved to about 1m.



But!

Few deformation in the tunnel!

No deformation of the rail track!

Kintai bridge
（Wooden bridge）
（Iwakuni city,
Yamaguchi Prif.）

Become steady by bend？

Peck's theory (to NATM)

Characteristic of flexible structure with thin-walled closed cross section

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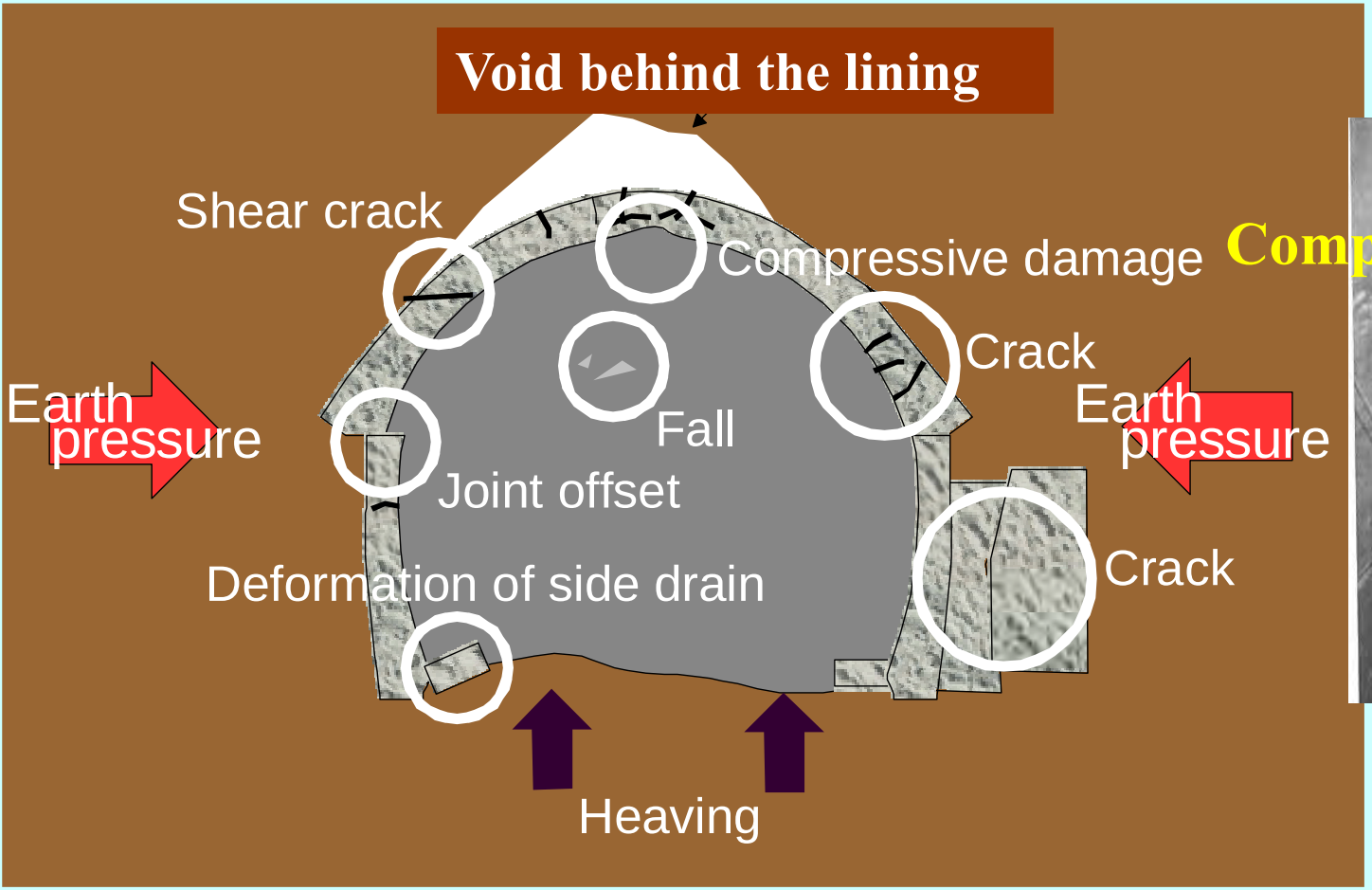
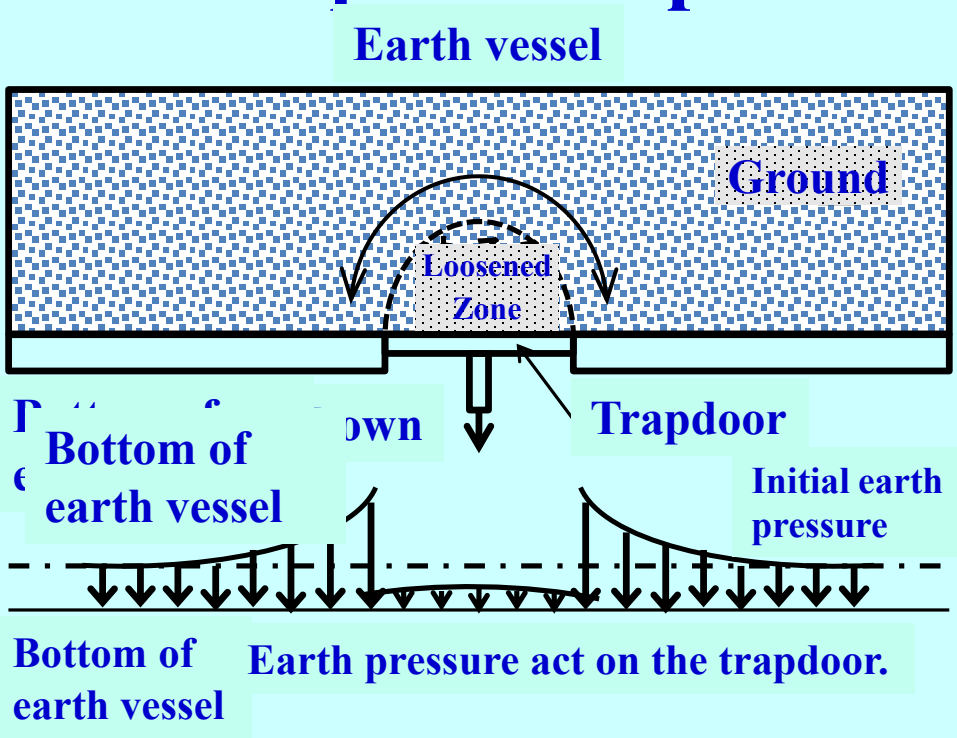


Tunnel requires support from surrounding ground

Trapdoor Experiment



Down a part of bottom earth vessel

Stress redistribution

Loosened zone was occurred at the downed part.

Redistribution of stress in the ground.

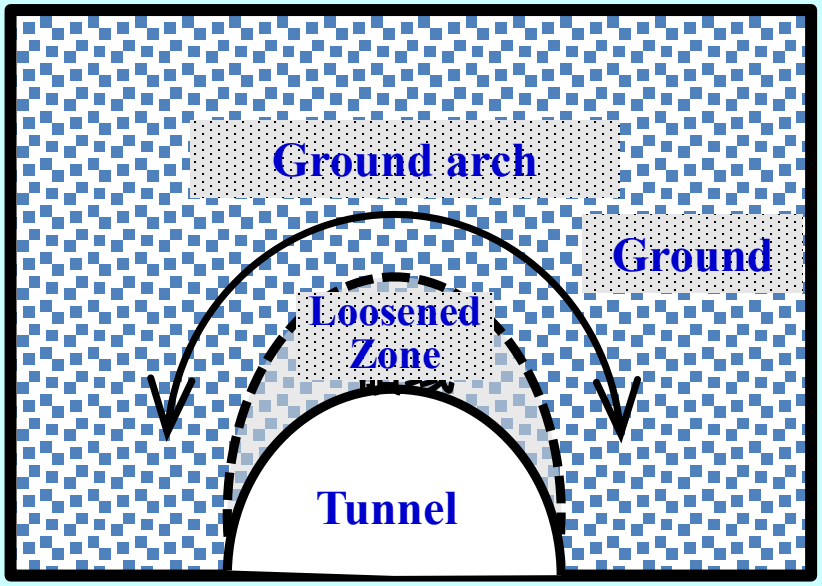
Outside of the losing zone works hard with arch shape.

（Ground arch）

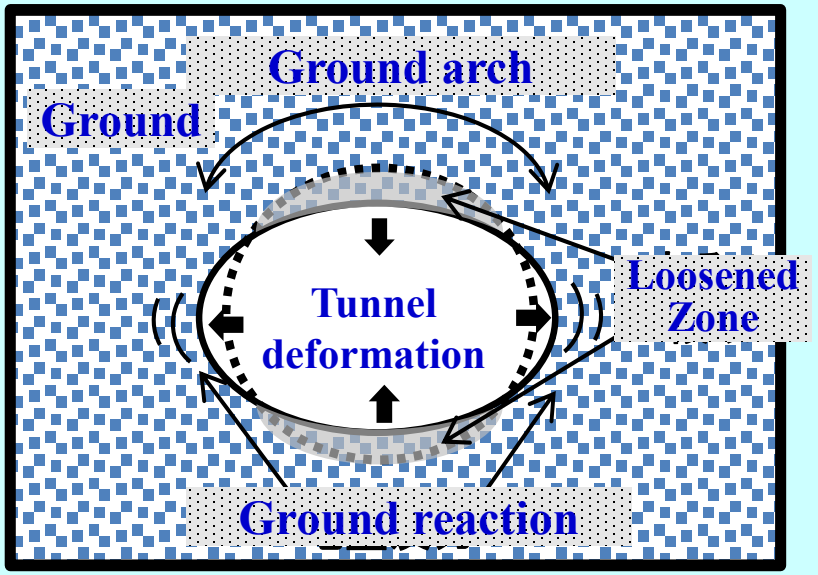
Support upper ground.

- Earth pressure acted on the bottom of the vessel rapidly reduced.
- At the both side of downed part, earth pressure increased.

Concept of ground arch



Bring out power of ground



Tunnel excavation

↓

Loosened Zone ← **Reasonable hard ground Overburden is over 1.5 to 2 times.**

↓

Redistribution of stress on outside of the loosened zone

↓

Only few upper load of ground act on the support and lining

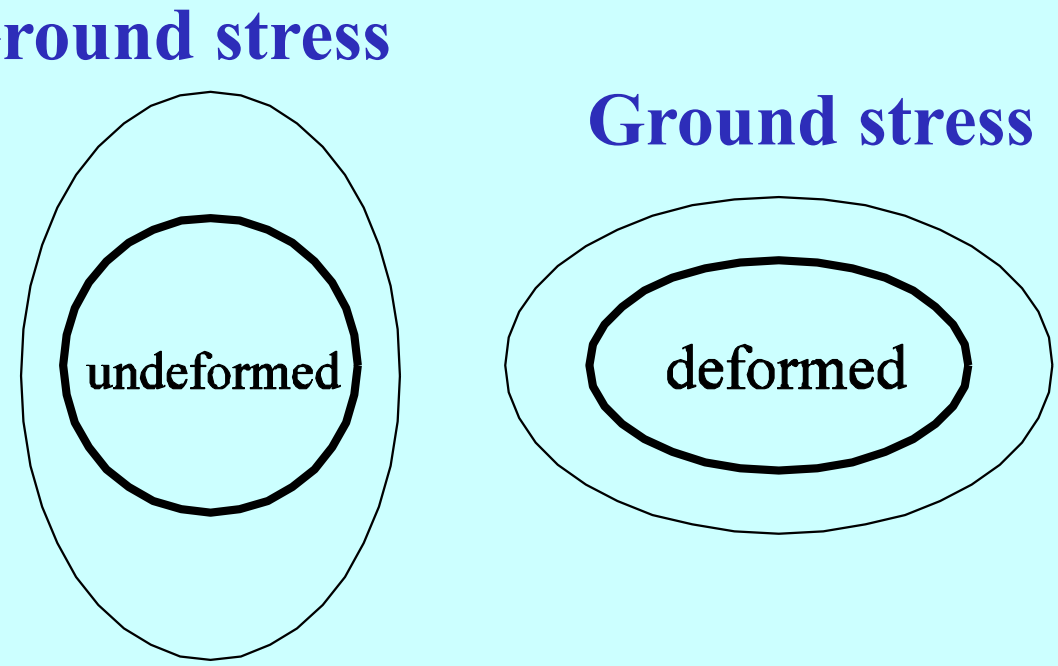
↓

Arch shape area which translates the upper ground load is formed.

（Ground arch or Arch action）

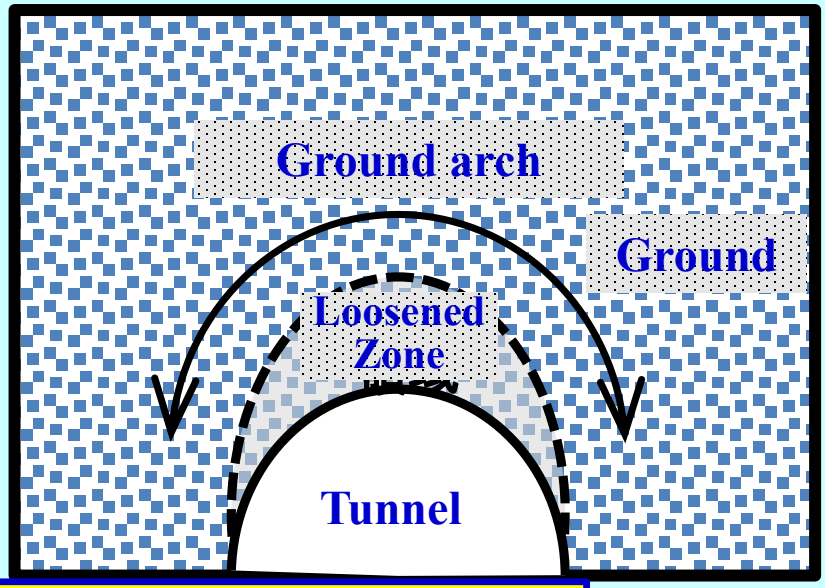
Stress redistribution

Peck(1969)



(a) initial stress (b) final stress

Concept of ground arch



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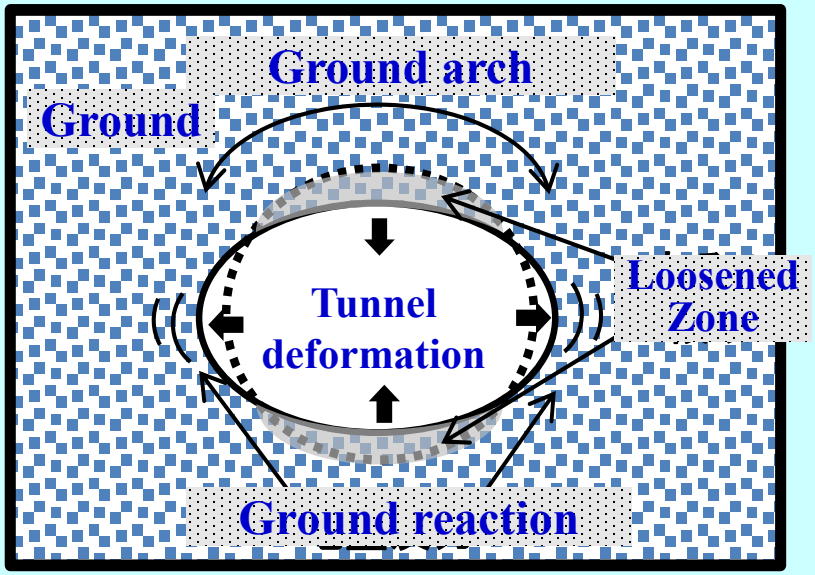


Vertical earth pressure （Ground arch or Arch action）

1. Total overburden pressure

（Load all overburden ground load）

2. Loosening earth pressure

（Load ground load of loosening zone, taking arch action into account

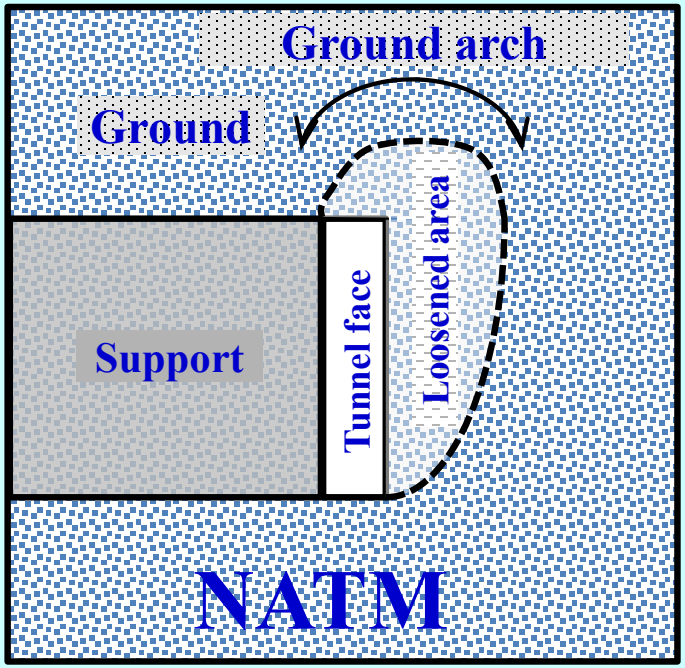
Lateral earth pressure

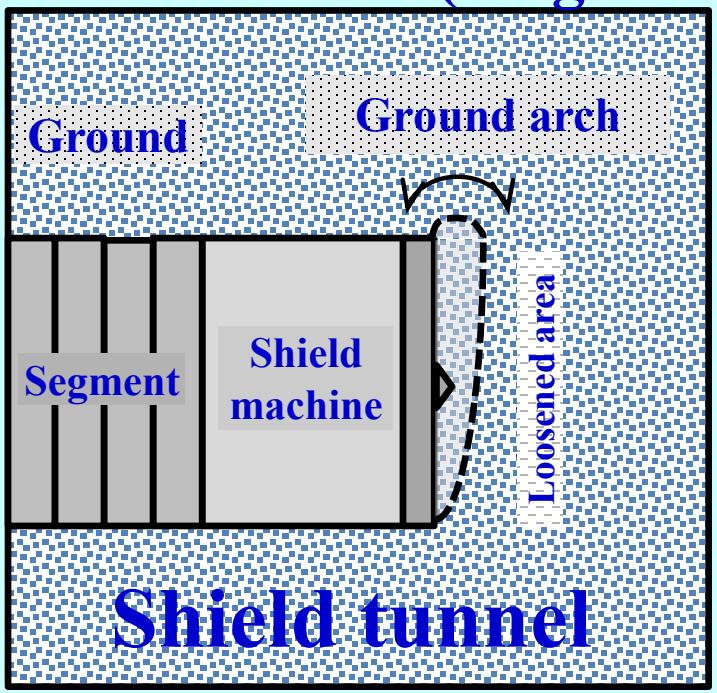
Multiply coefficient,0.35−0.85 and vertical earth pressure

（The harder ground is, the smaller coefficient become）

Ground stability on longitudinal direction

Concept of stress redistribution on tunnel head (longitudinal)





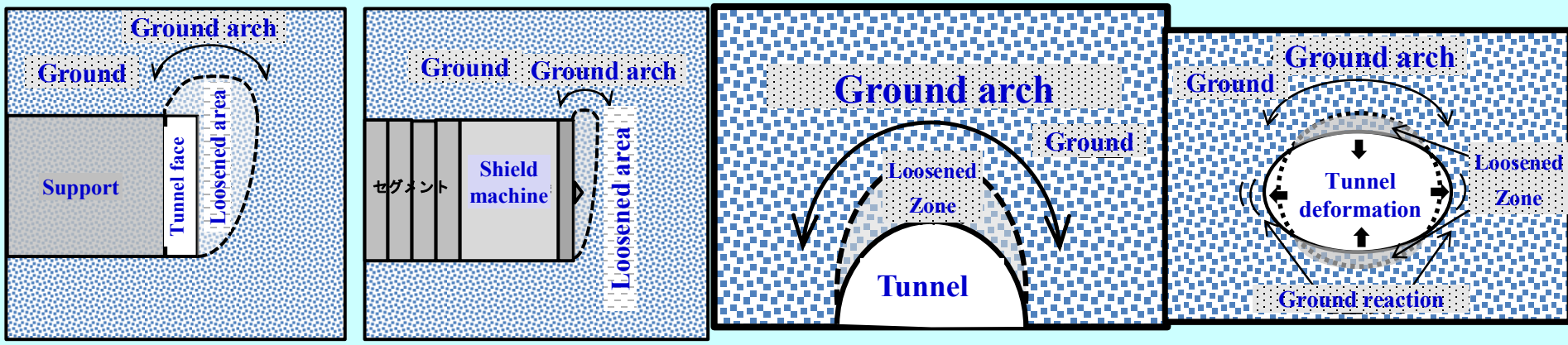
Stability of tunnel head on longitudinal direction is needed

Loosened zone occurs in forward ground of tunnel face.

Face collapse⇒tunnel support and lining collapse

Support part or shield machine and ground in front of tunnel face hold out, and ground arch is formed above loosened zone.

Concept of ground arch(Cross･Longitudinal deflection)



Loosened area at tunnel face influence to stability of 3 dimension and cross section.

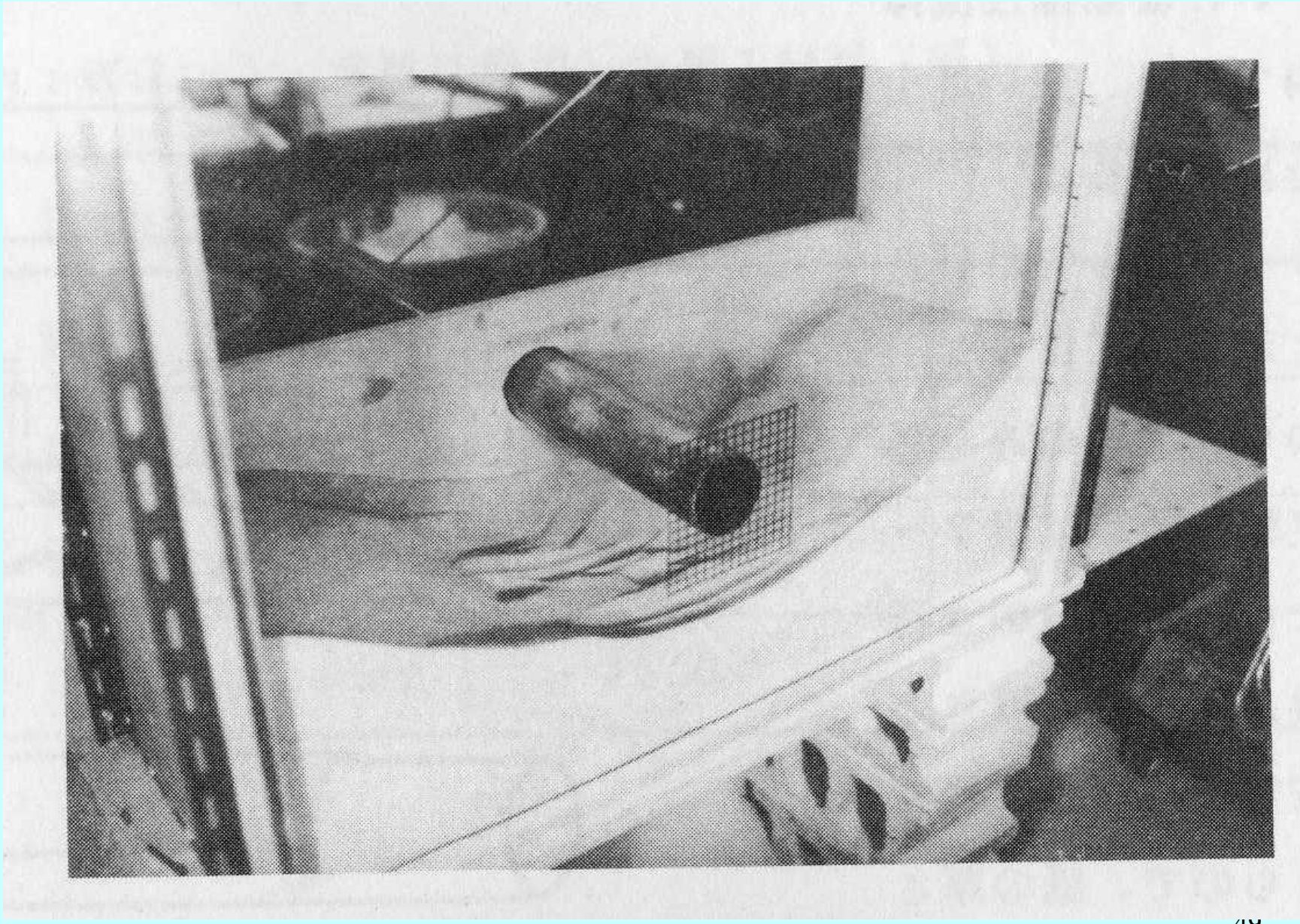
Design: Necessary to consider influence by 3 dimension.

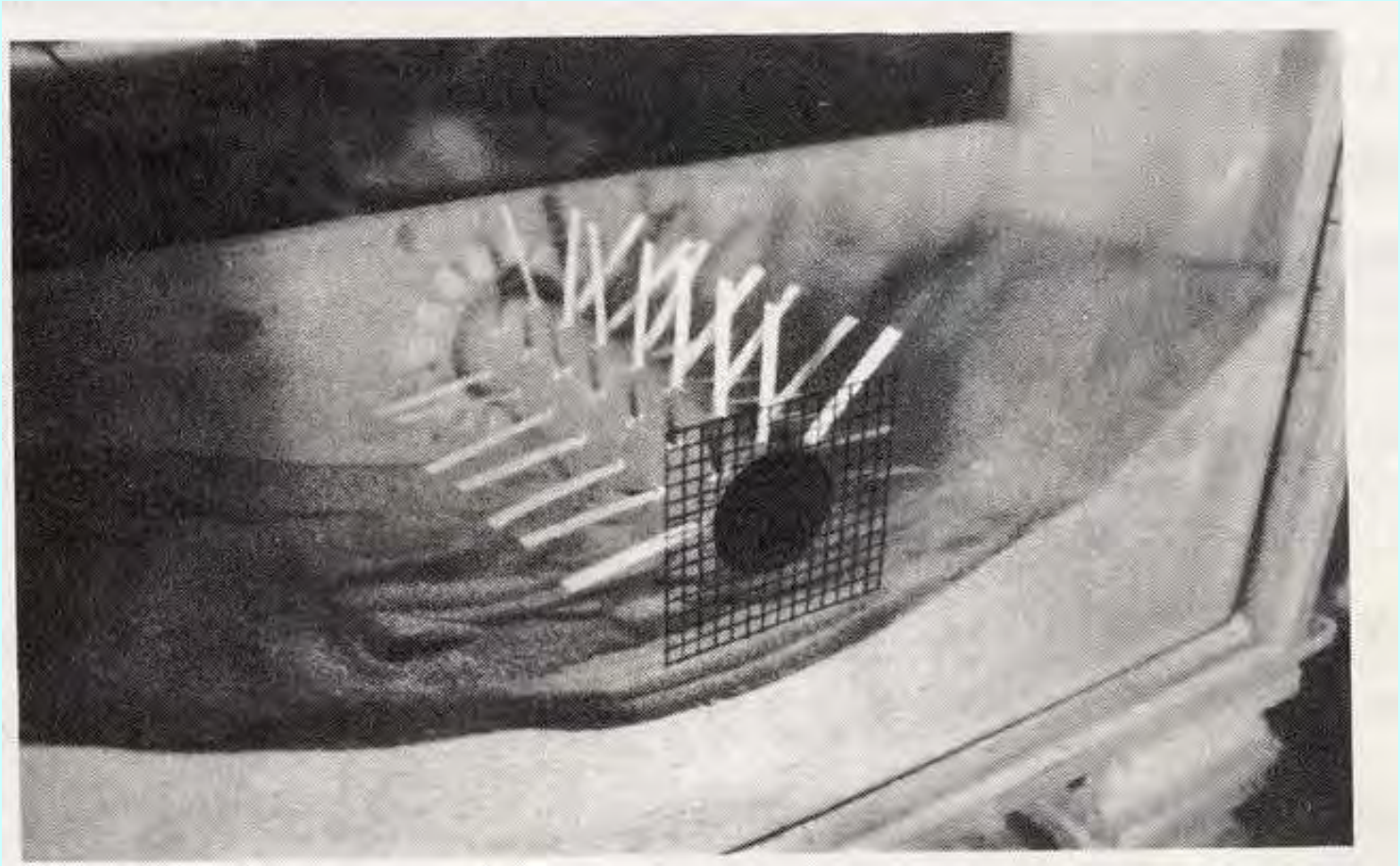
Express with stress release ratio

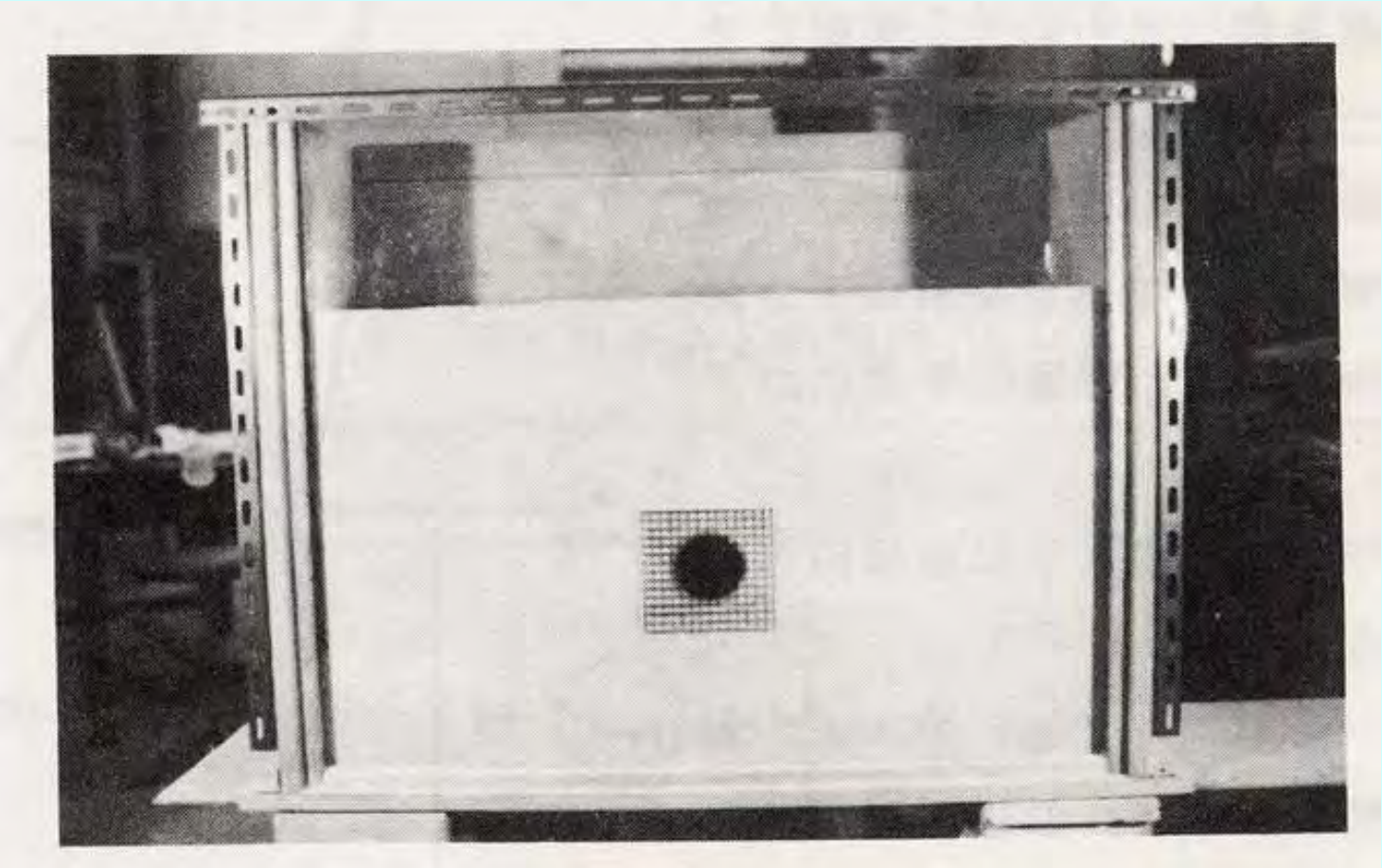
Analysis by 3 dimension FEM analysis.

Face stability affects to selection of construction method.

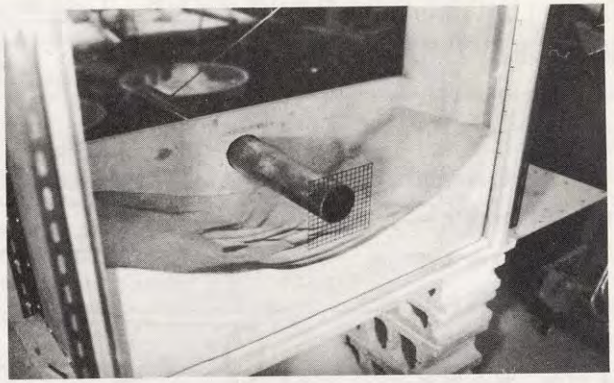
Selection of construction method is one of the design.



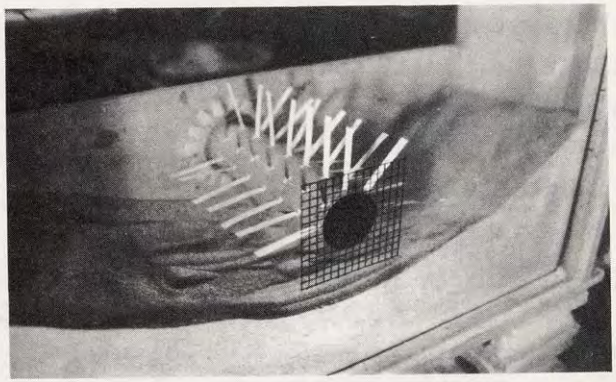




(a)



(b)



(c)

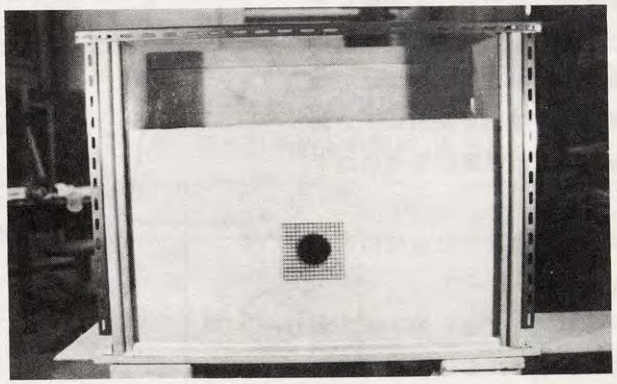


写真７－１　実験手順

Lining materials for experiments. (paper)

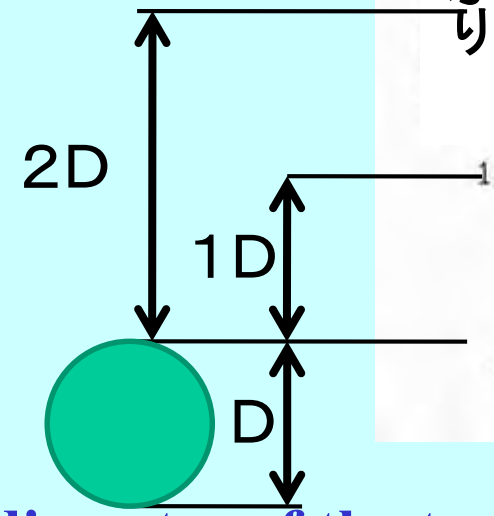
	Paper type	weight (g/m^2)	thickness (mm)
No.1	Kent paper	154.3	0.180
No.2	tracing paper	60.0	0.058
No.3	tracing paper	50.0	0.050
No.4	tracing paper	40.0	0.045

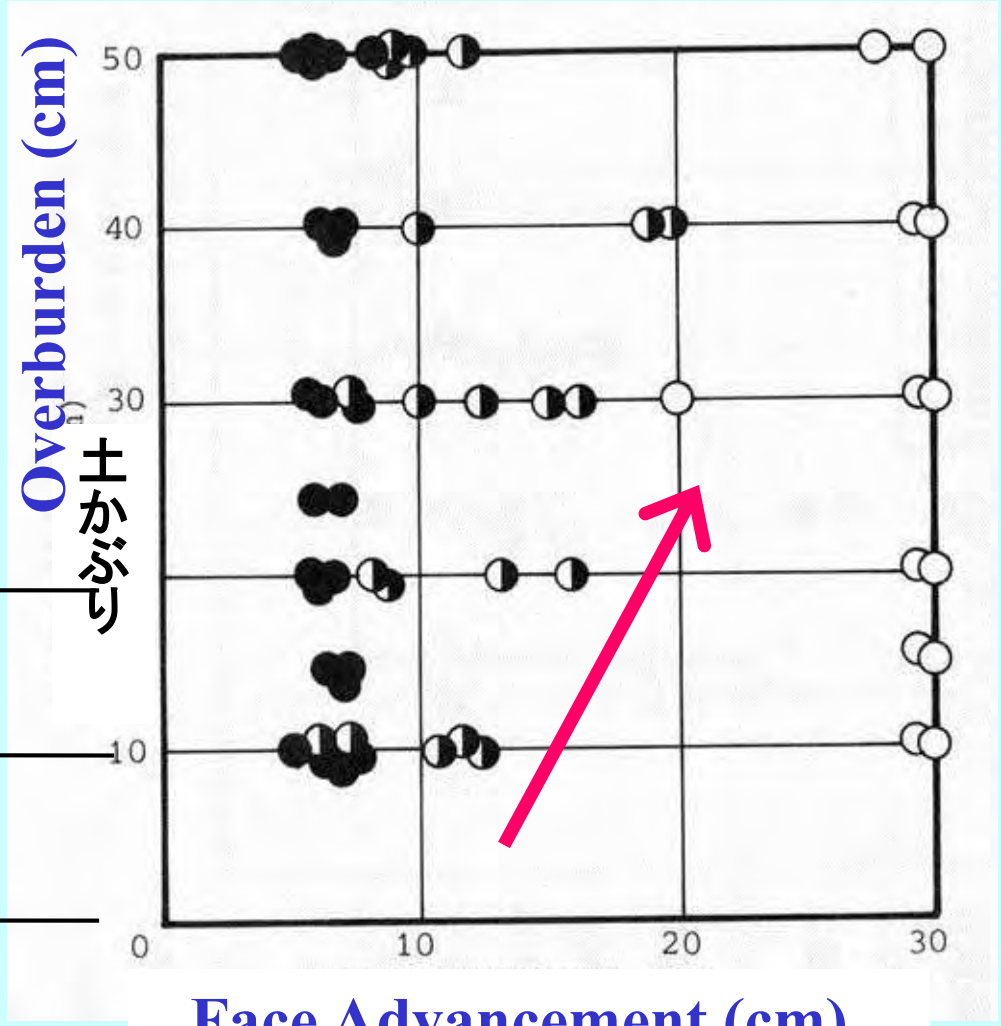
Relationship between Overburden and Face Advancement (cm)

Legend

- ○ Thick paper
- ◔ A little thin paper
- ● Thin paper

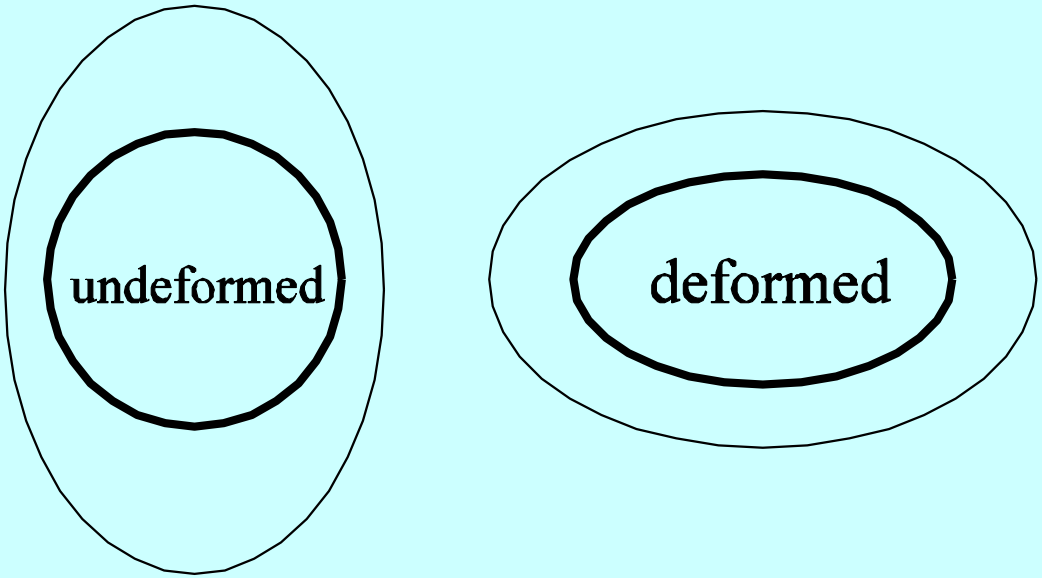
When overburden is small, the tunnel is week





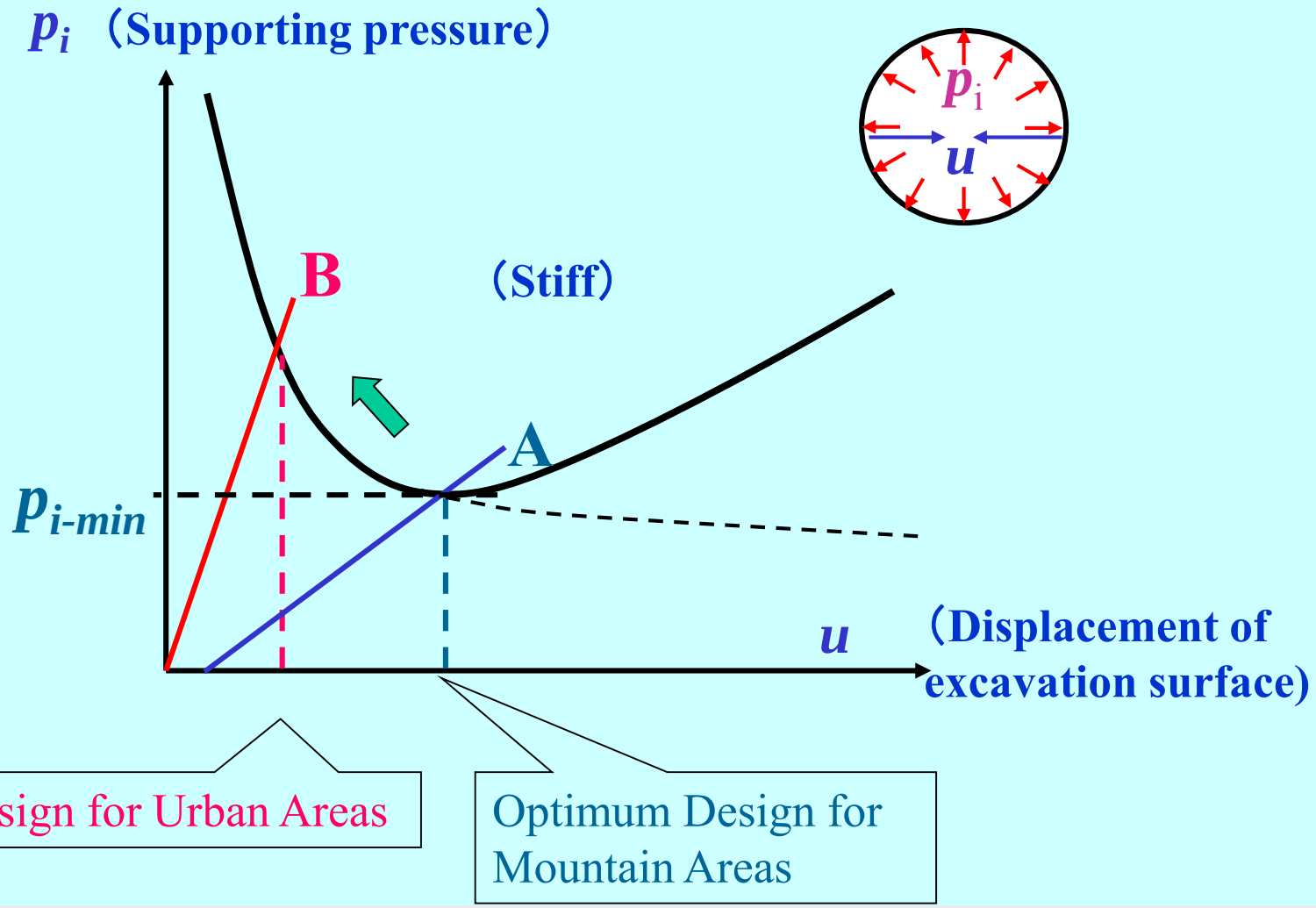
D means diameter of the tunnel

Peck（1969）



(a) initial stress　　(b) final stress

① Protect Loosing

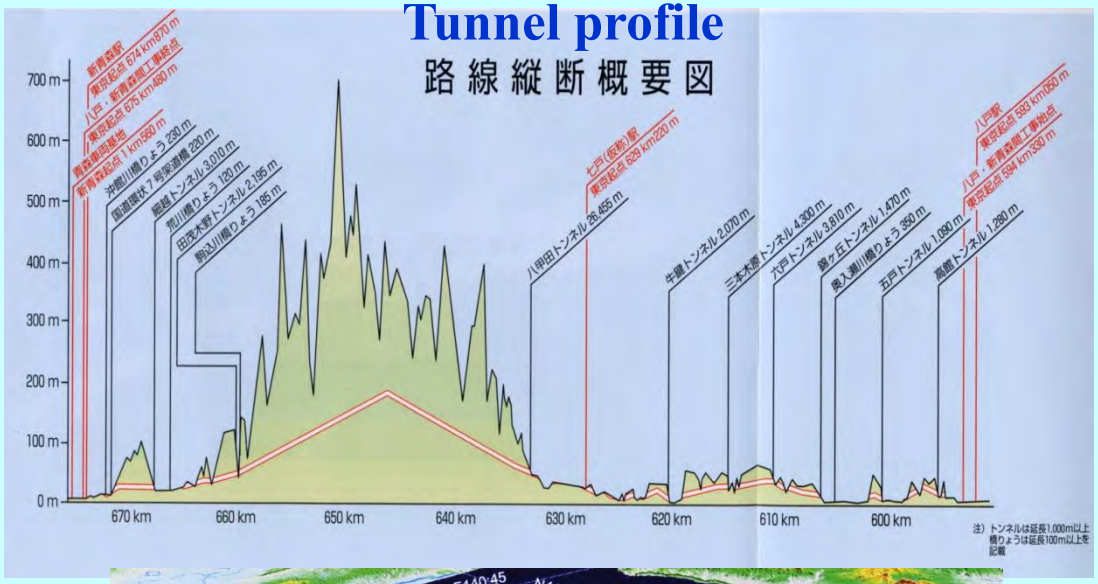


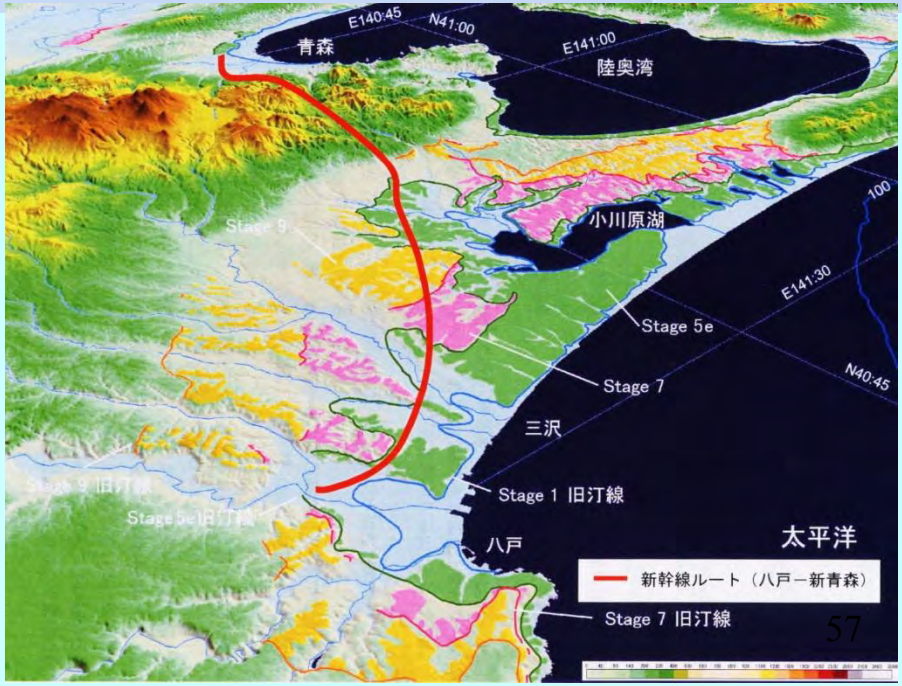
Conceptual diagram of ground and support characteristic curve (Fenner-Pacher Curve)

A example of tunnel construction

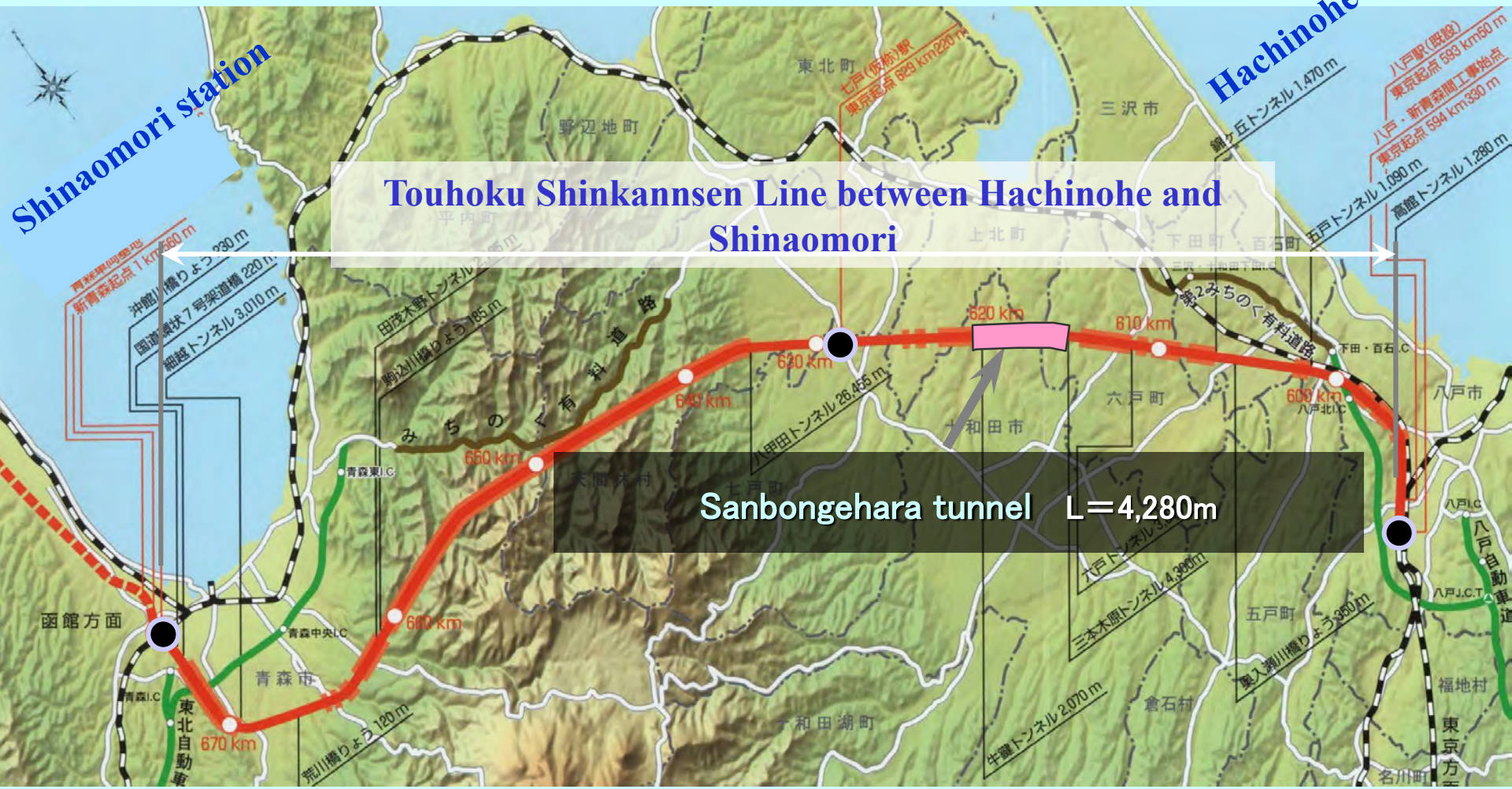
Tohoku Shinkansen Line

Tunnel profile





Outline of Sanbongihara tunnel

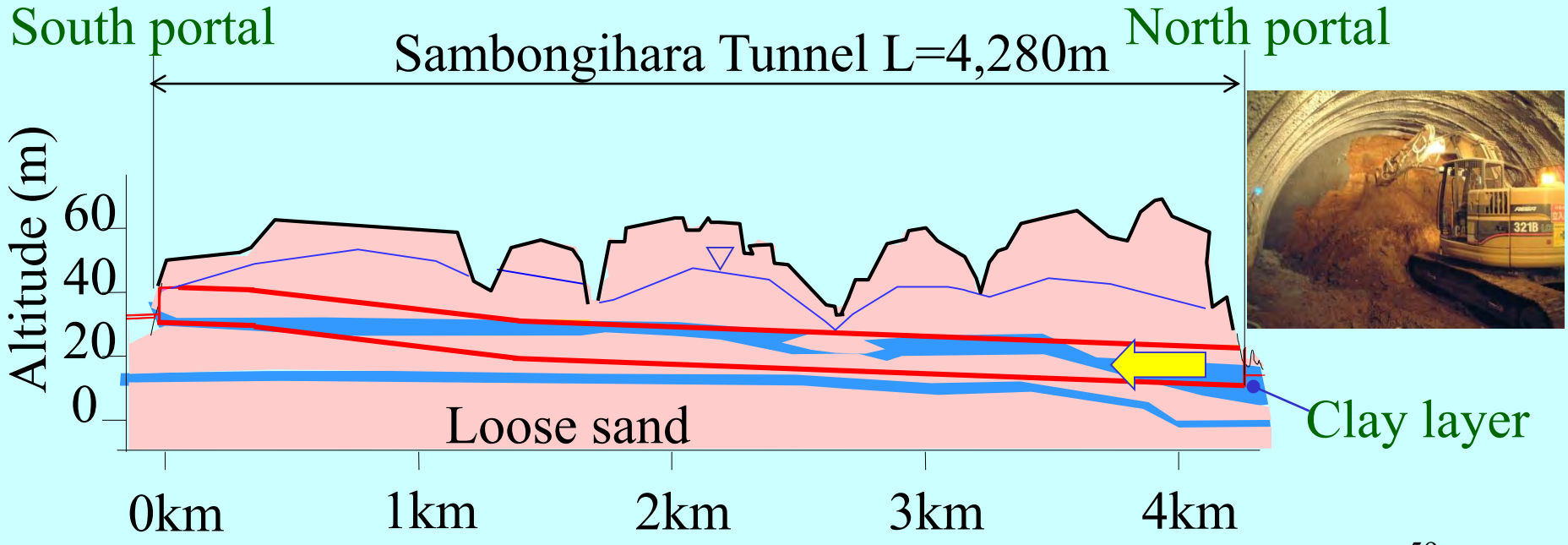


Geological profile of Sambongihara Tunnel

- Sambongihara Tunnel
  - Tunnel cover is Shallow
  - Ground : Diluvial loose sand with a clay layer
  - Ground water level: High

} throughout the tunnel

➡ Very severe construction conditions



- Excavation by NATM started from the North portal on Jul., 2002

For constructing with NATM

Excavation method

Short Bench Cut method

Auxiliary method

Water inflow control

Deep well, Well point method

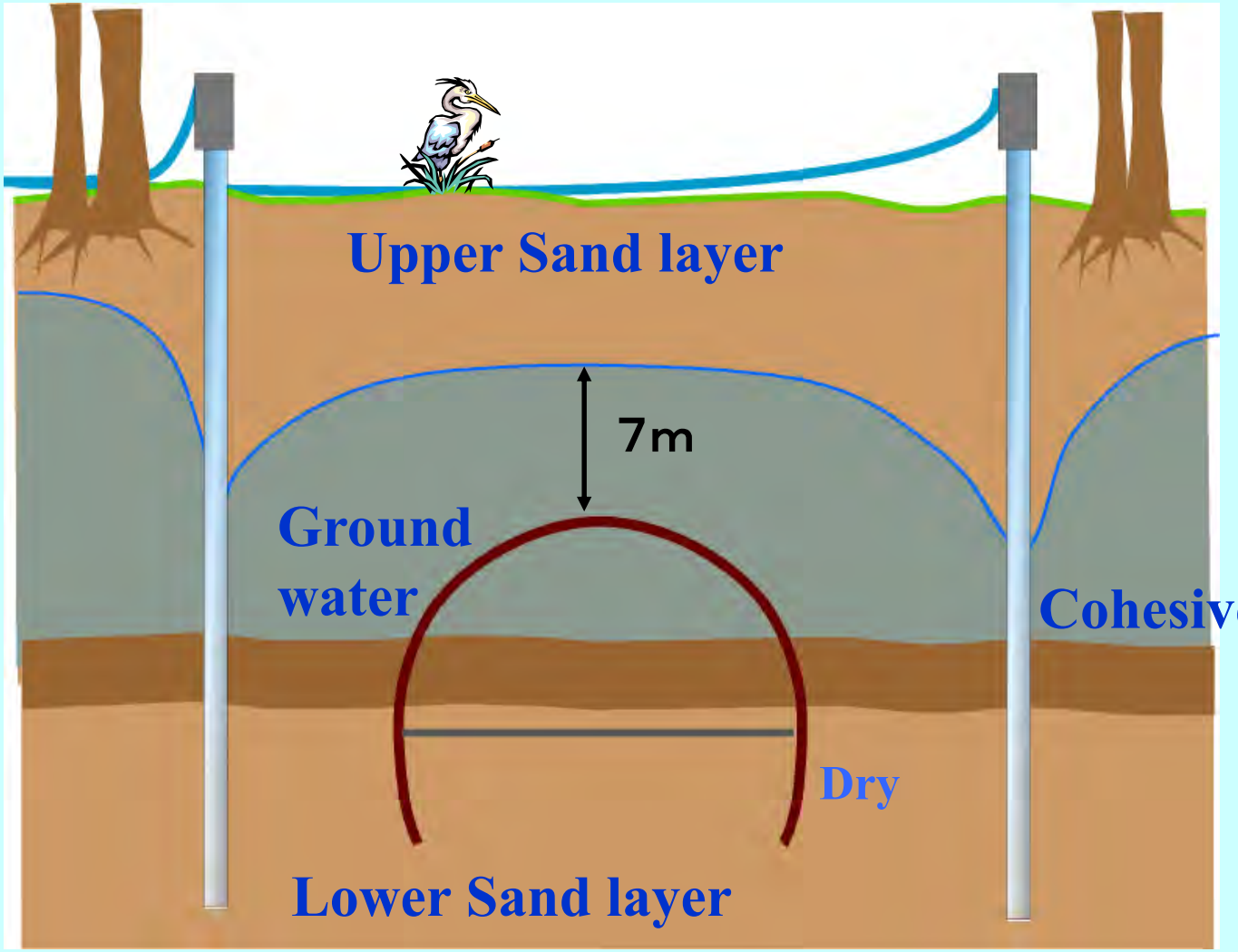
Presupport

Grouting type forepoling

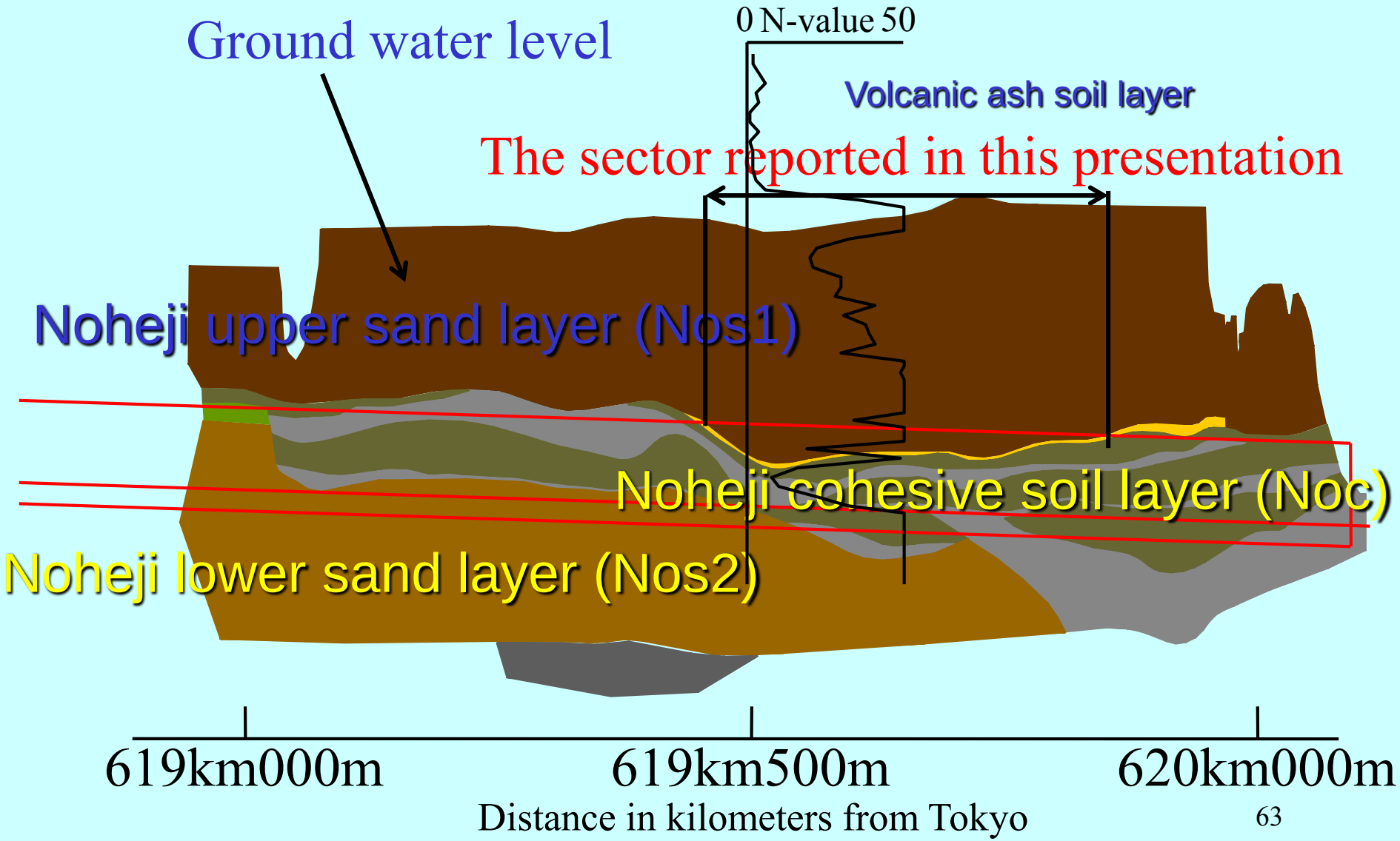
Deep well

Deep well

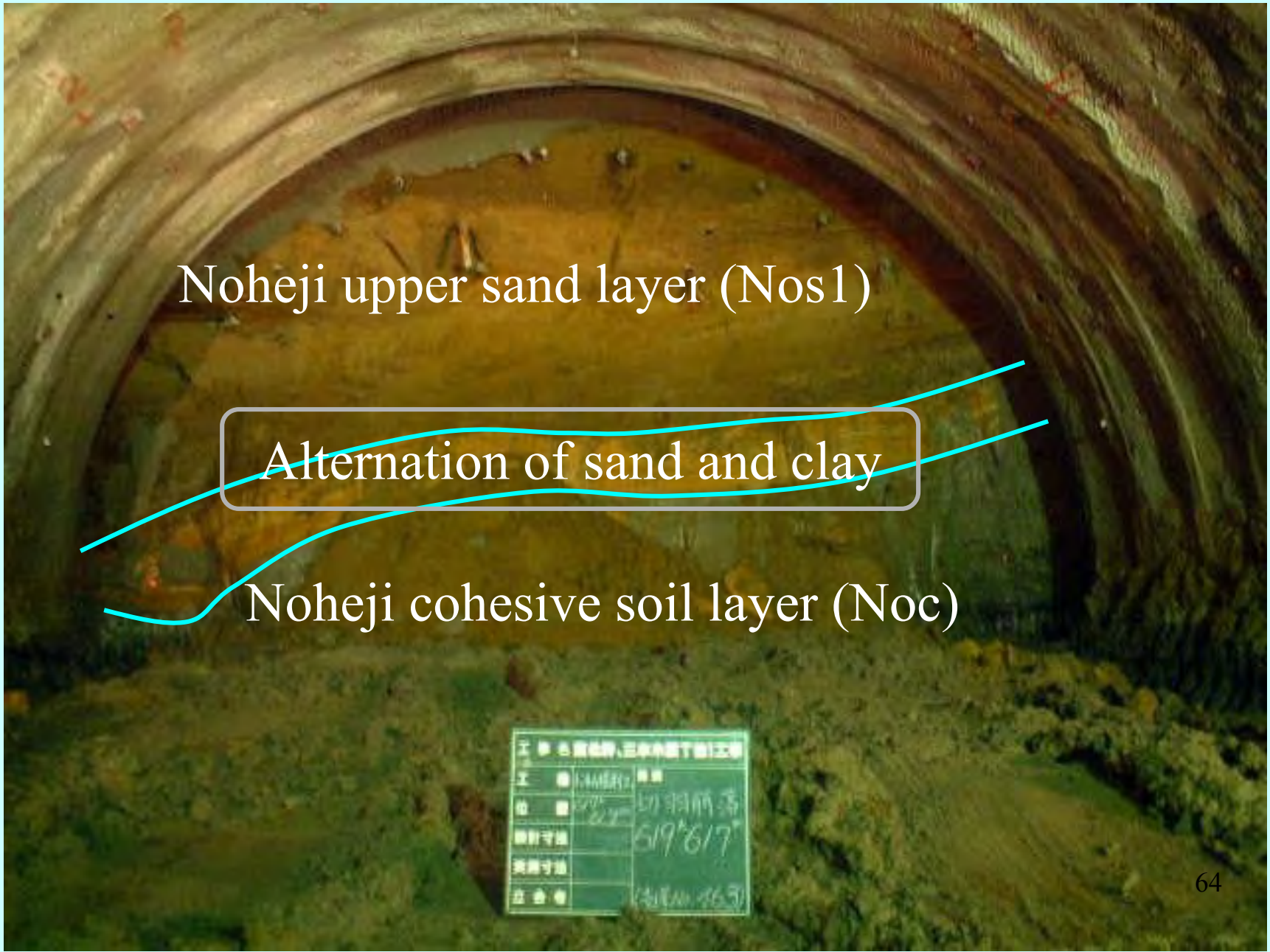
Deep well



Abstract of the topography and the geological feature

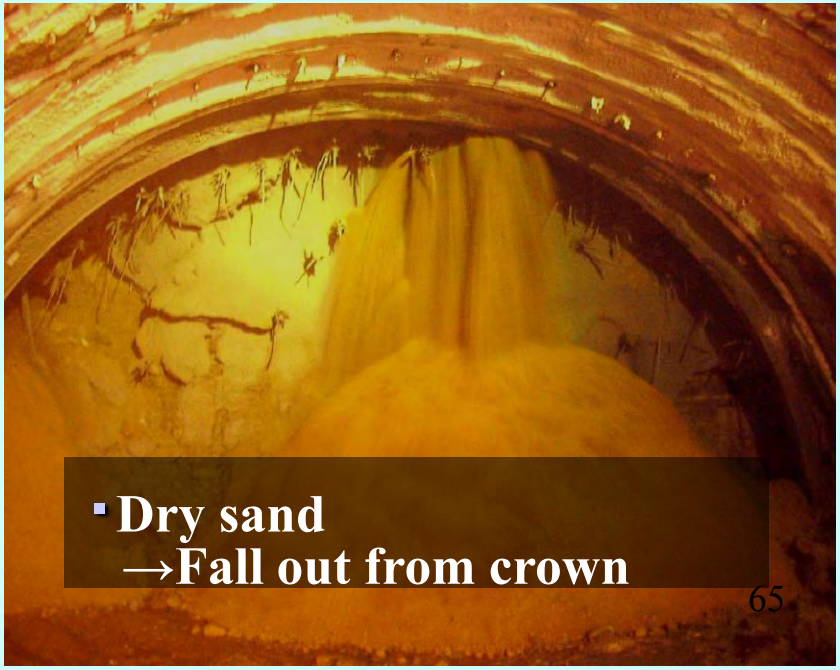


Photograph of a face



Remain ground water

→Face break down and flow out



- Dry sand
  →Fall out from crown

Problem of NATM

- NATM
  - NATM has excellent flexibility to ground condition.
  - Face is not supported during excavation
  - The safety decreases especially in a soft ground.

- Sambongihara Tunnel
  - Two large collapse in one year
  - Delay of construction work

New construction method was required to improve the safety of excavation and the construction speed.


再 生
9:35:44AM

New construction method "SENS" system

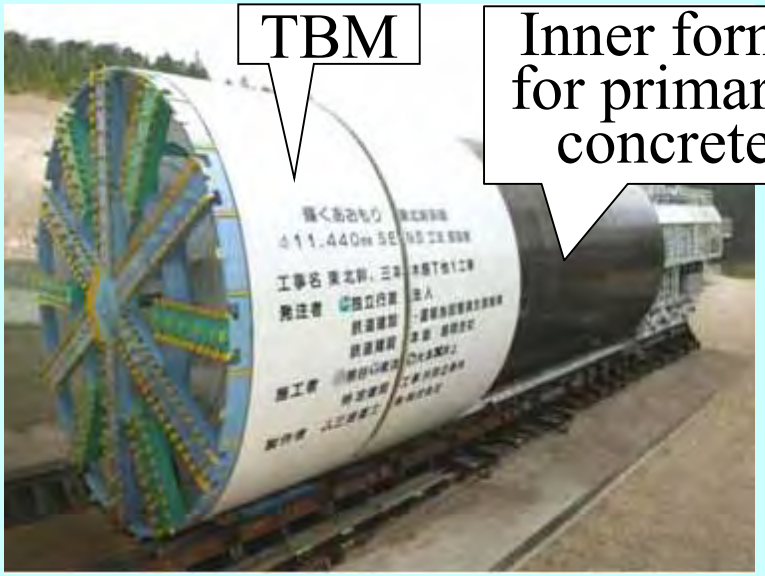
SENS method

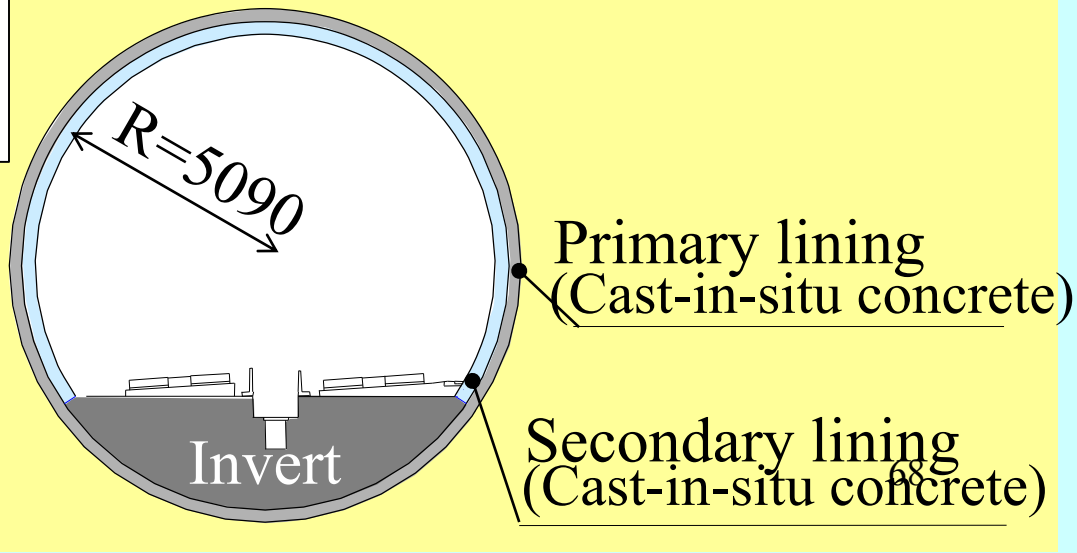
New tunnel construction method which is able to improve the safety, economy and workability of the construction.

S: "Shield tunneling method"
E: "Extruded concrete lining"
N: "NATM"
S: "System"

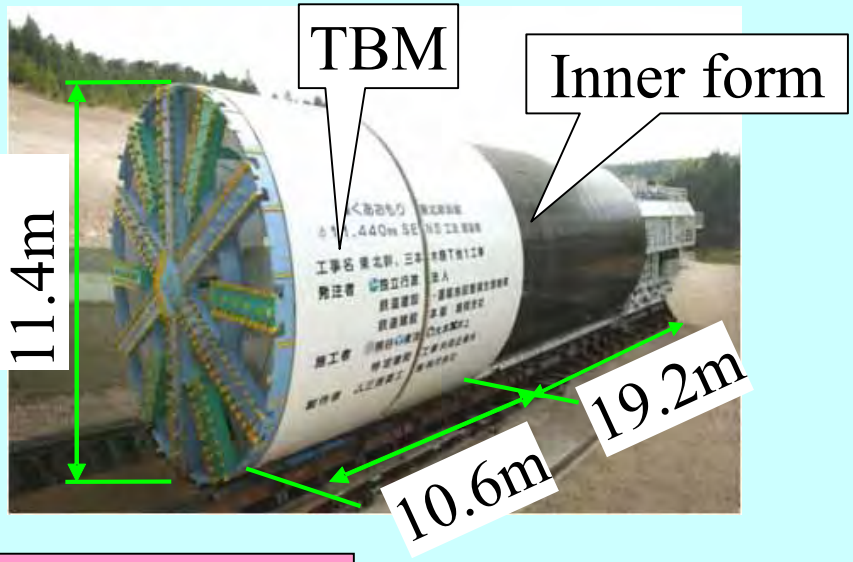
In SENS method;

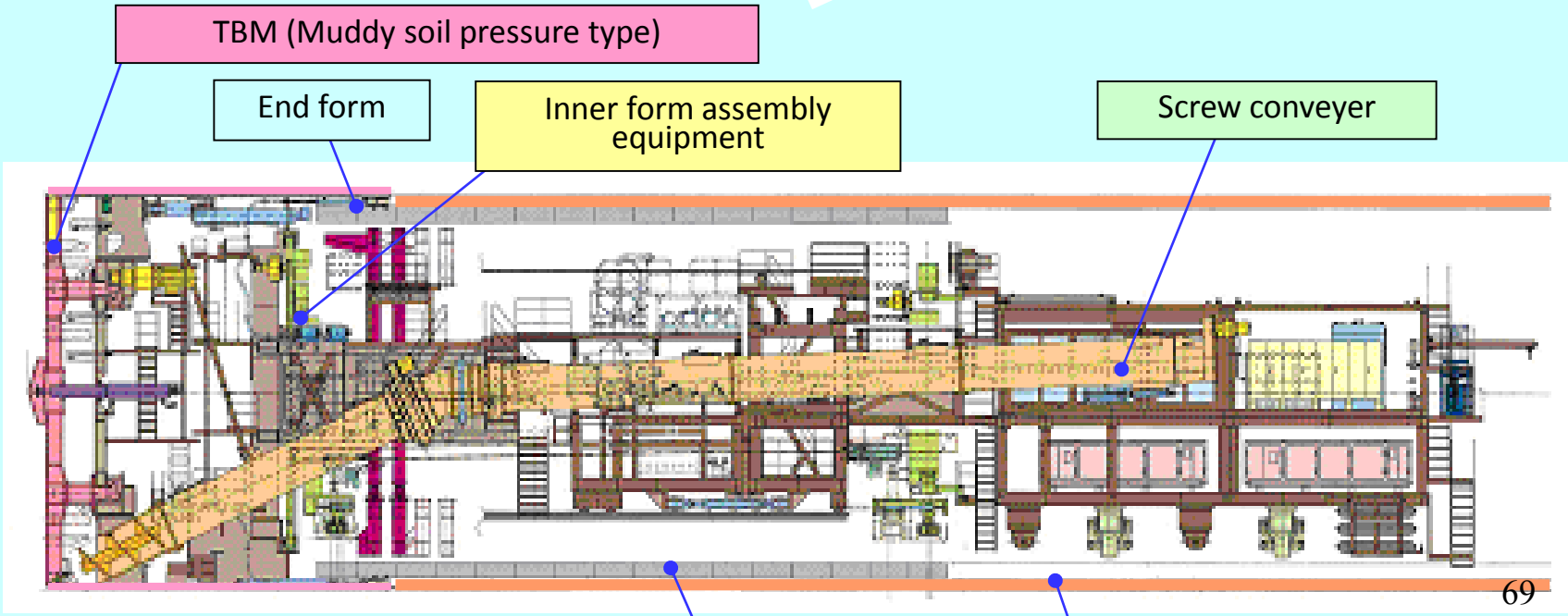
- Tunnel: Bored by TBM
- Primary lining: Cast-in-situ concrete instead of precast segment
- Secondary lining: Cast-in-situ concrete for finishing





Facilities of SENS system





South portal

Sambongihara Tunnel L=4,280m

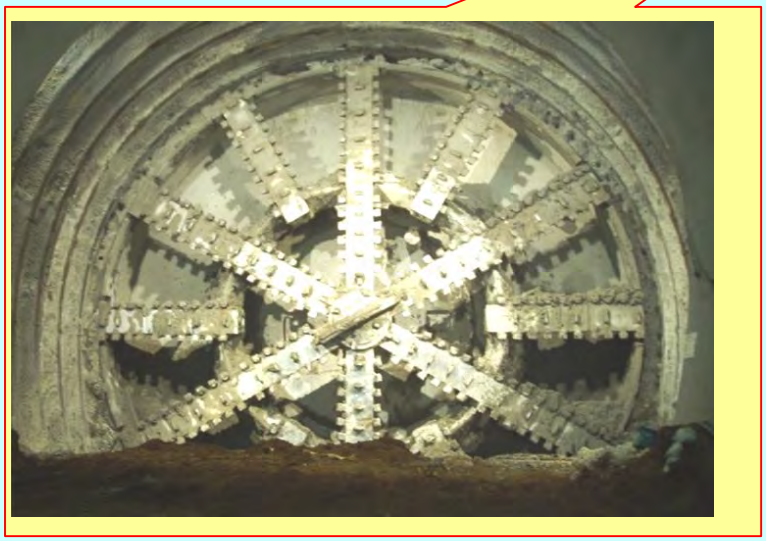
North portal

TBM L=3,015m

NATM L=1,265m

Loose sand

Clay layer

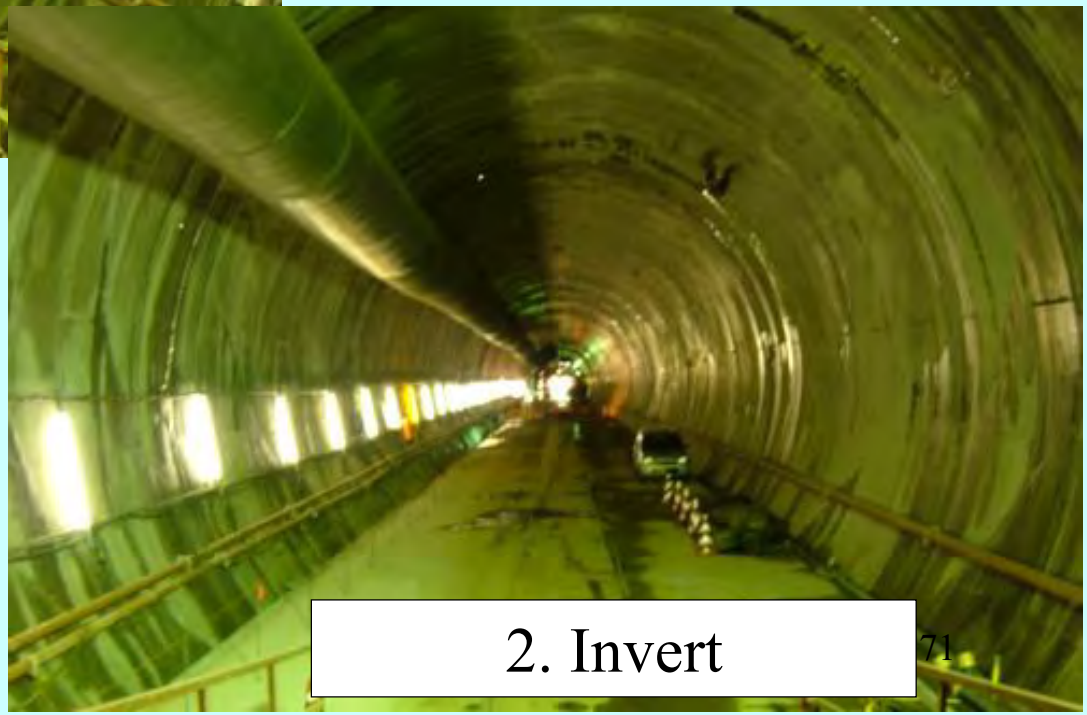


- Remaining 3015m was excavated by SENS (TBM) method
- Excavation by NATM was terminated on Jul., 2004

- Tunnel was bored through in Nov, 2006

Building process

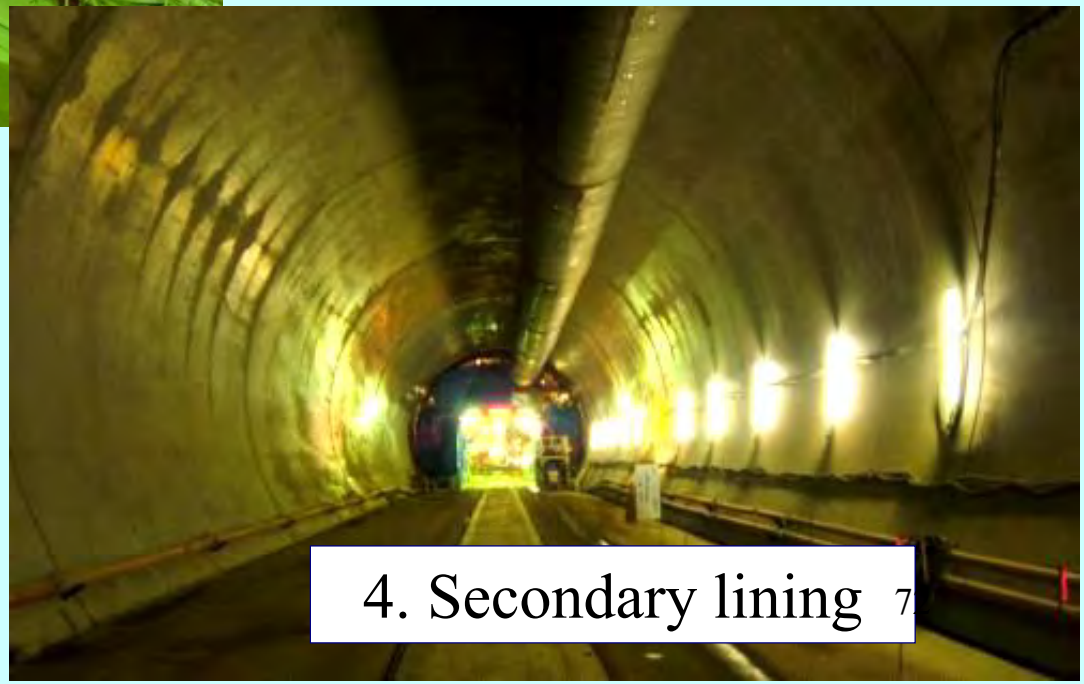
1. Primary lining



2. Invert

Building process

3. Waterproof sheet

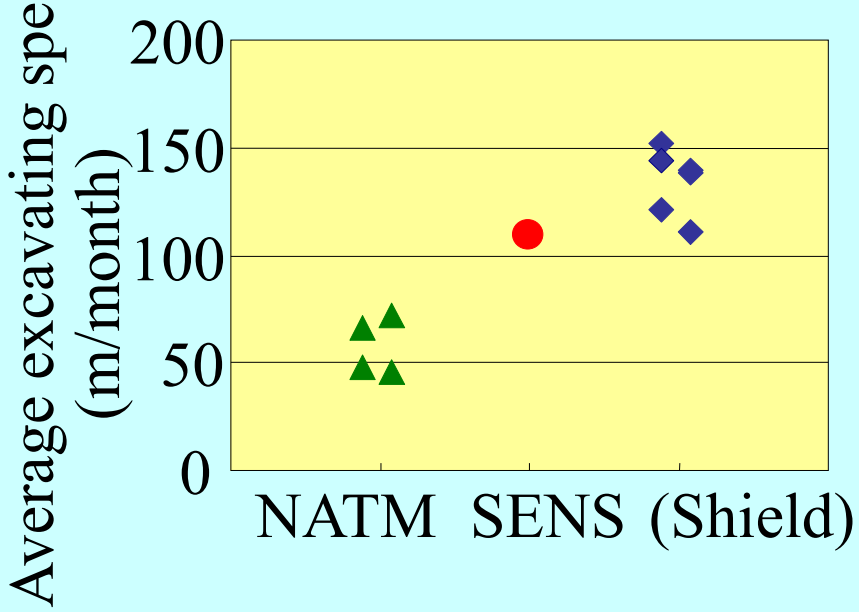


4. Secondary lining

Comparison between NATM and Shield

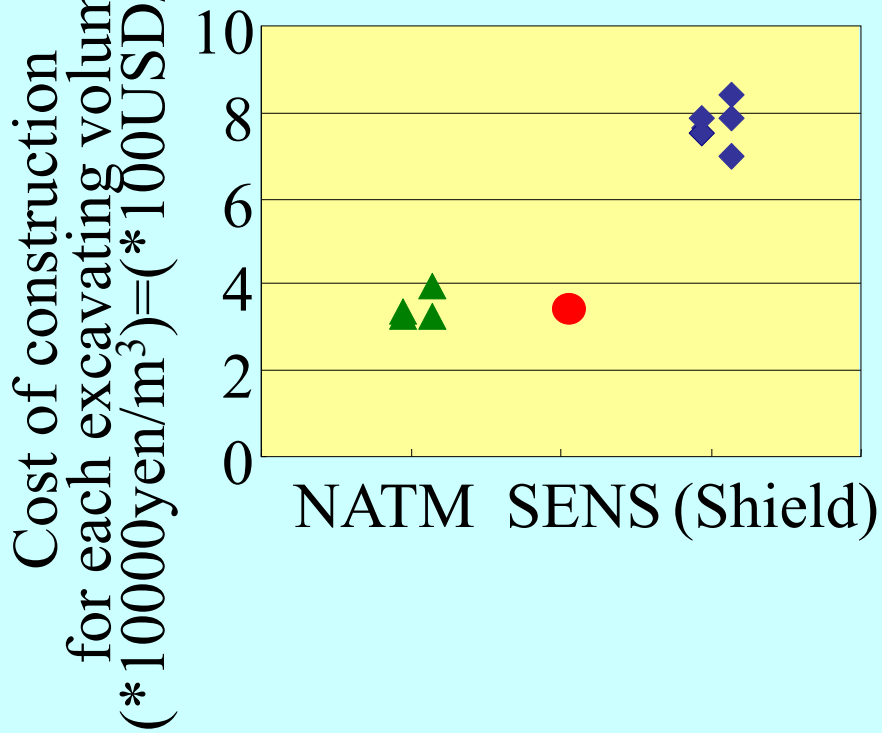
Average excavating speed

- Twice faster than NATM



Construction cost

- Cost of construction for unit excavation volume is almost the same



➡ SENS method is effective in improving the excavating speed.

Conclusion

SENS method

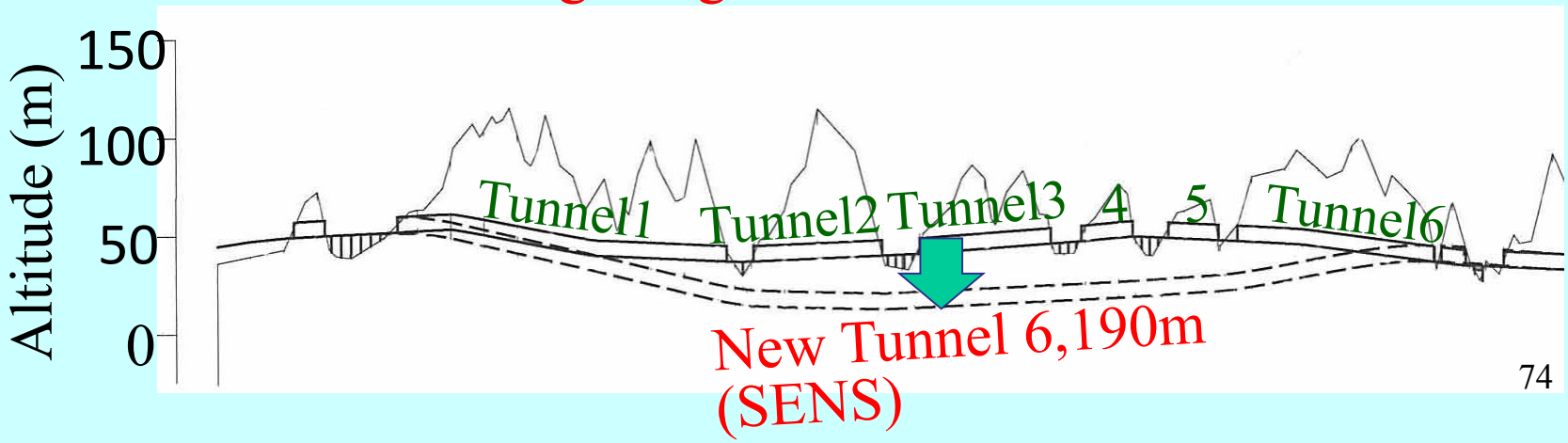
- Having a good performance in Sambongihara Tunnel
- Applied to Tsugaru-Yomogita Tunnel of the Hokkaido Shinkansen Line

Tsugaru-Yomogita tunnel

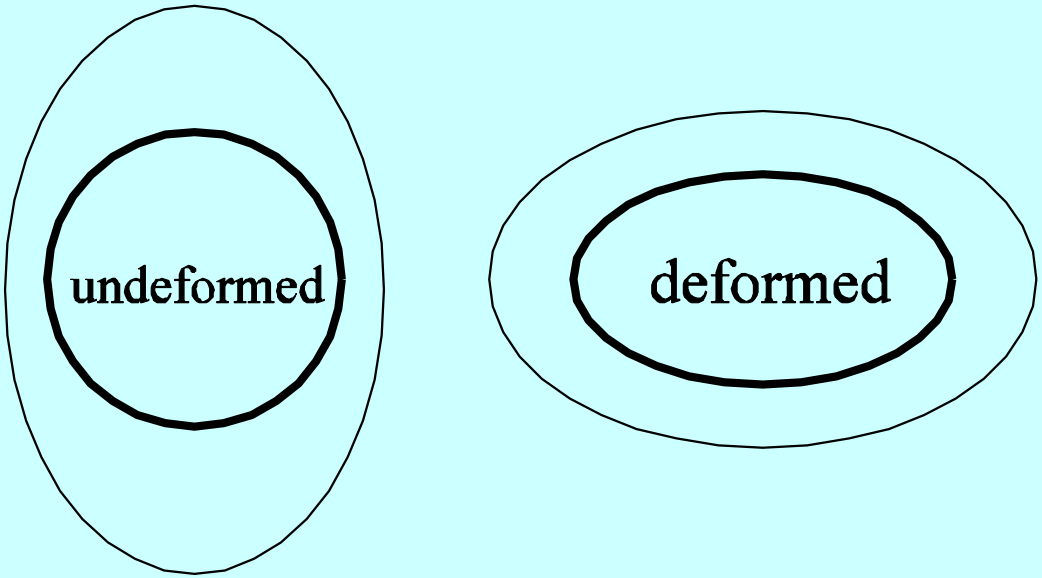
- Tunnel cover is shallow.
- Ground is a diluvial loose sand and the ground water level is high.

} throughout the tunnel

- 6 tunnels were brought together in one tunnel.

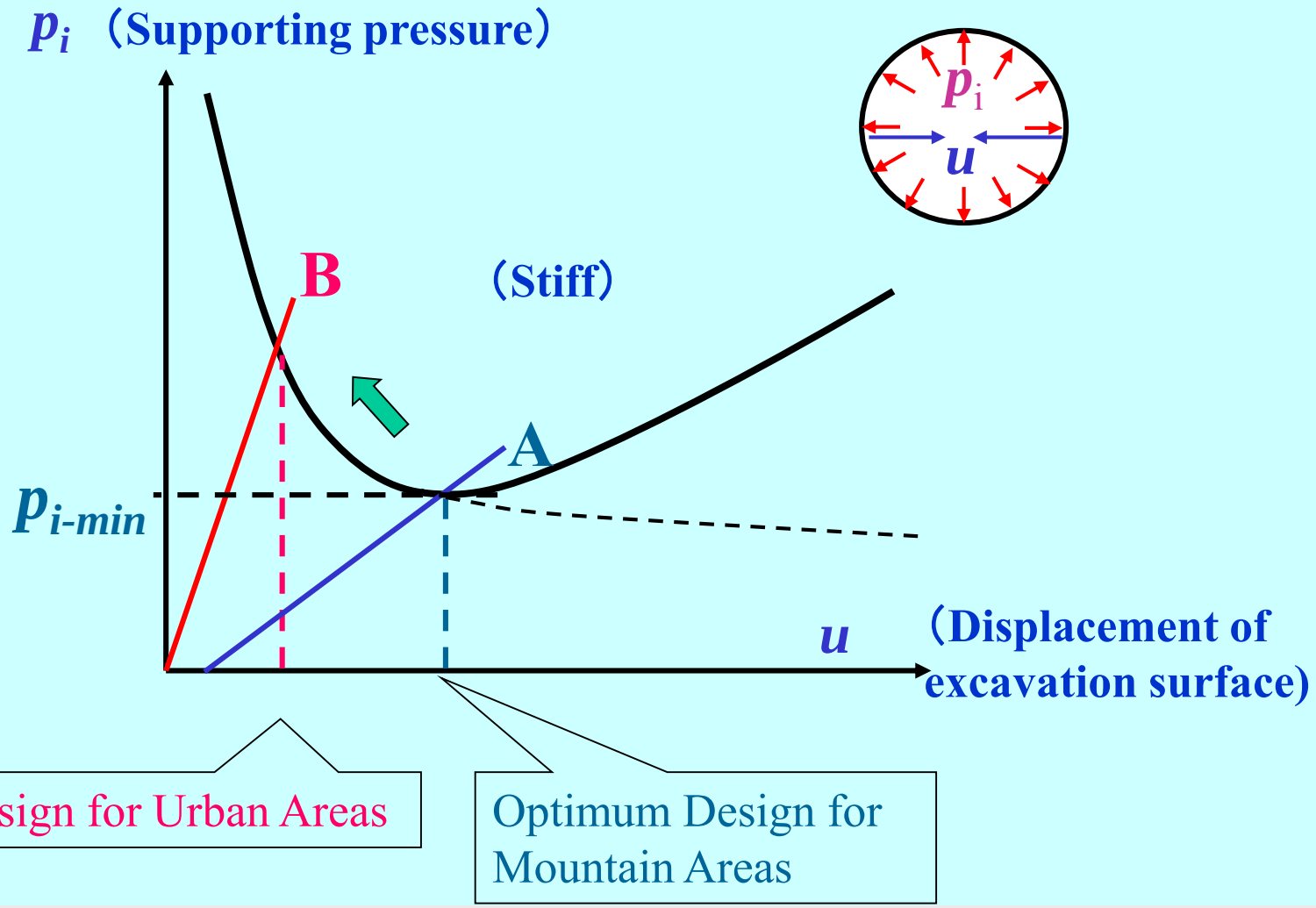


Peck（1969）



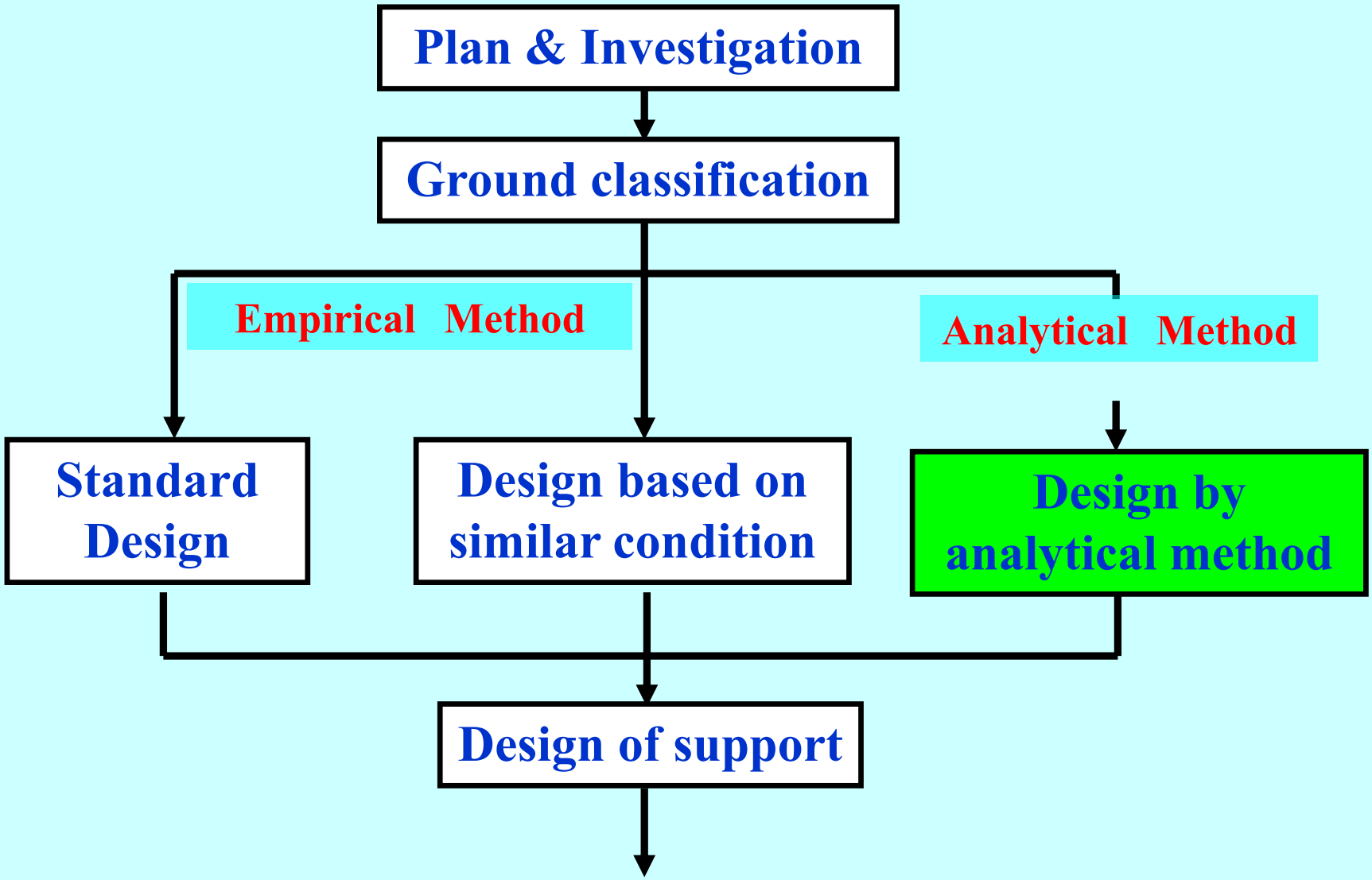
(a) initial stress　　(b) final stress

① Protect Loosing

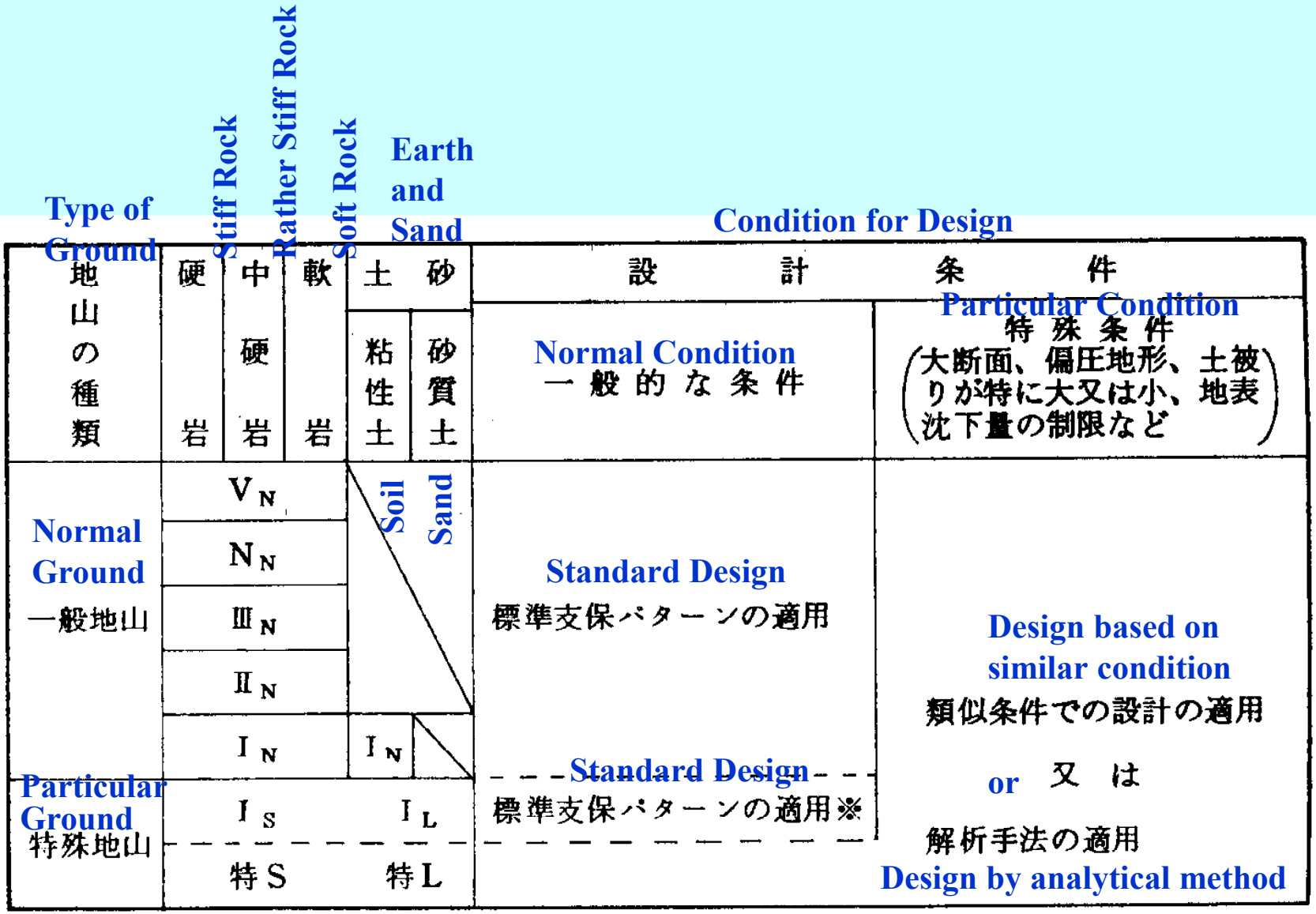


Conceptual diagram of ground and support characteristic curve (Fenner-Pacher Curve)

Flowchart of Design



Relationship between Ground Type and Design Methods of Tunnels



A example of design by analytical method
（Elasto-plastic finite element method）

1. Simulation of Construction Procedure ⇨ Check on Construction Procedure

2. Decision on a shape of the tunnel cross section, Check on safety of the shape and size of designed tunnel members, Estimate for the ground movement due to excavation, etc.

3. Deformation of cross sections (Settlement of crown, rising of invert), Extent of the plastic area, Stress of supporting parts.
   → Check on safety of ground and supporting members

4. Evaluation method of characteristic of ground and rock isn't established yet.
   → Combine with results of the rock test, soil test and site test .

Kyobashi tunnel in Keiyou line

Widened part from tunnel to station

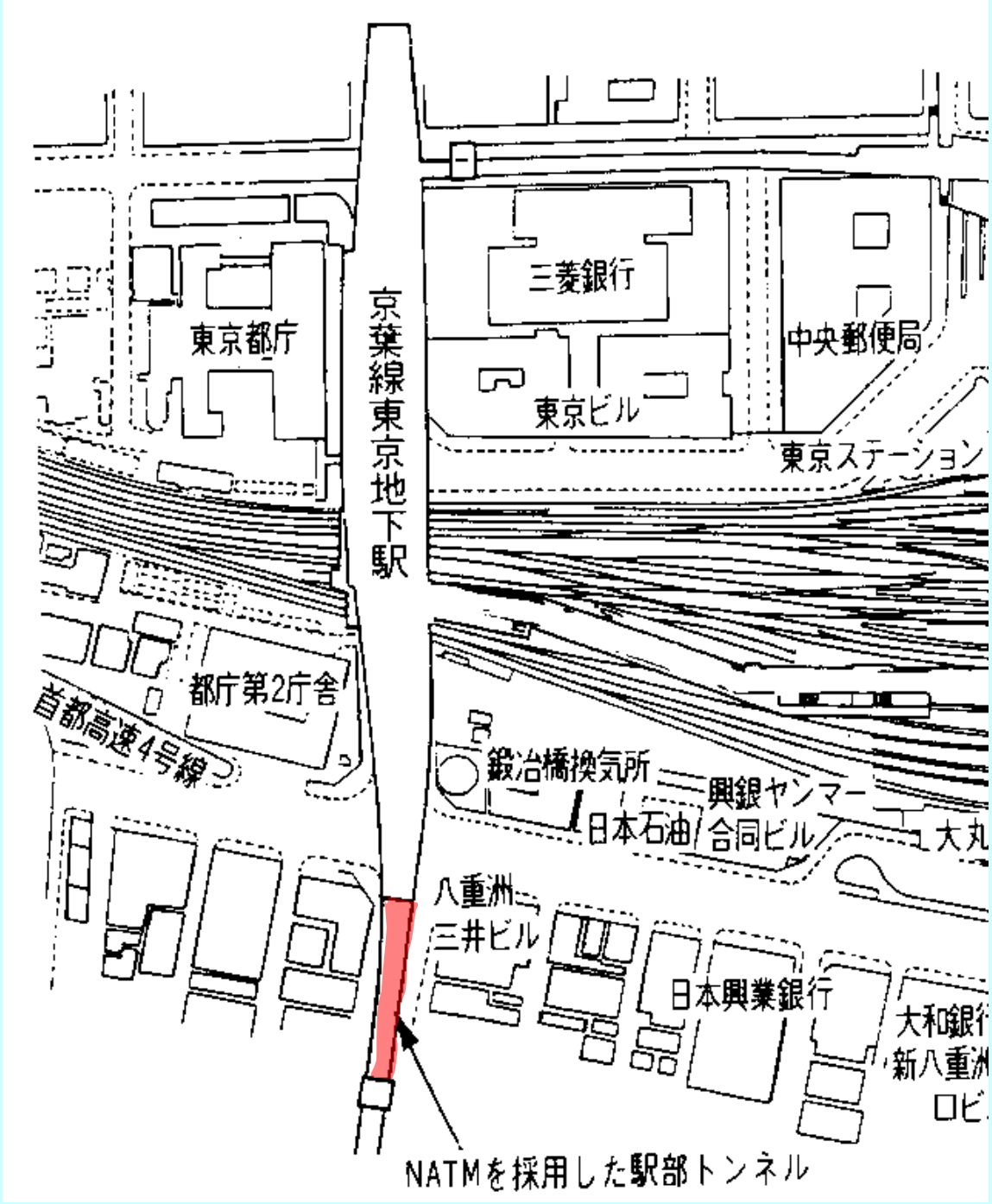
Cross section of excavation : Double tracks-4 tracks

Flatness H/B＝over 0.8
Length 72.65m
Overburden 25m
Diluvial layer, Edogawa layer, N-value:80, Sandy soil with hard clay layer.

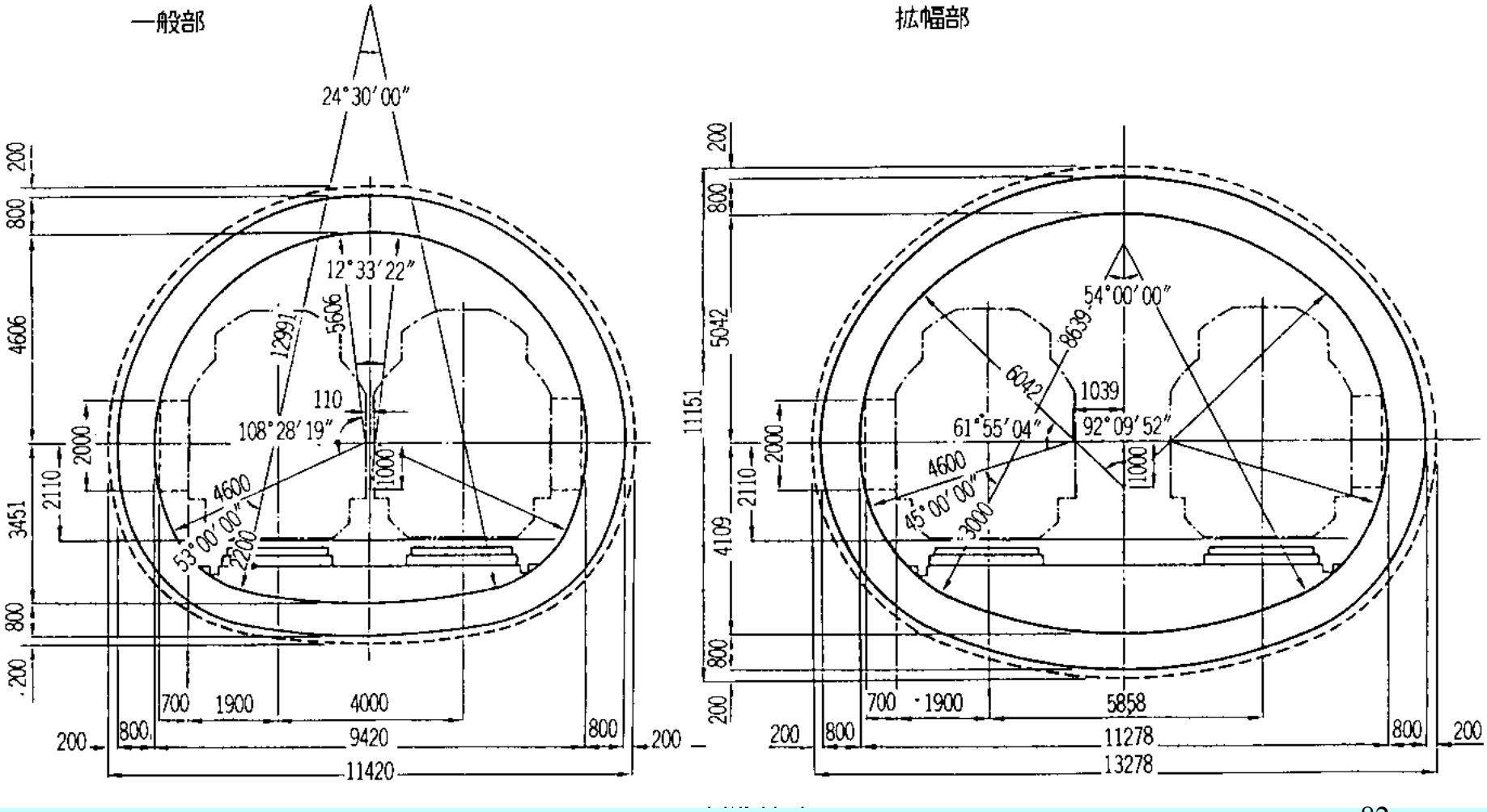
Elasto-plastic finite element method

Criterion of construction management → Estimate of impact on surrounding structures and environment

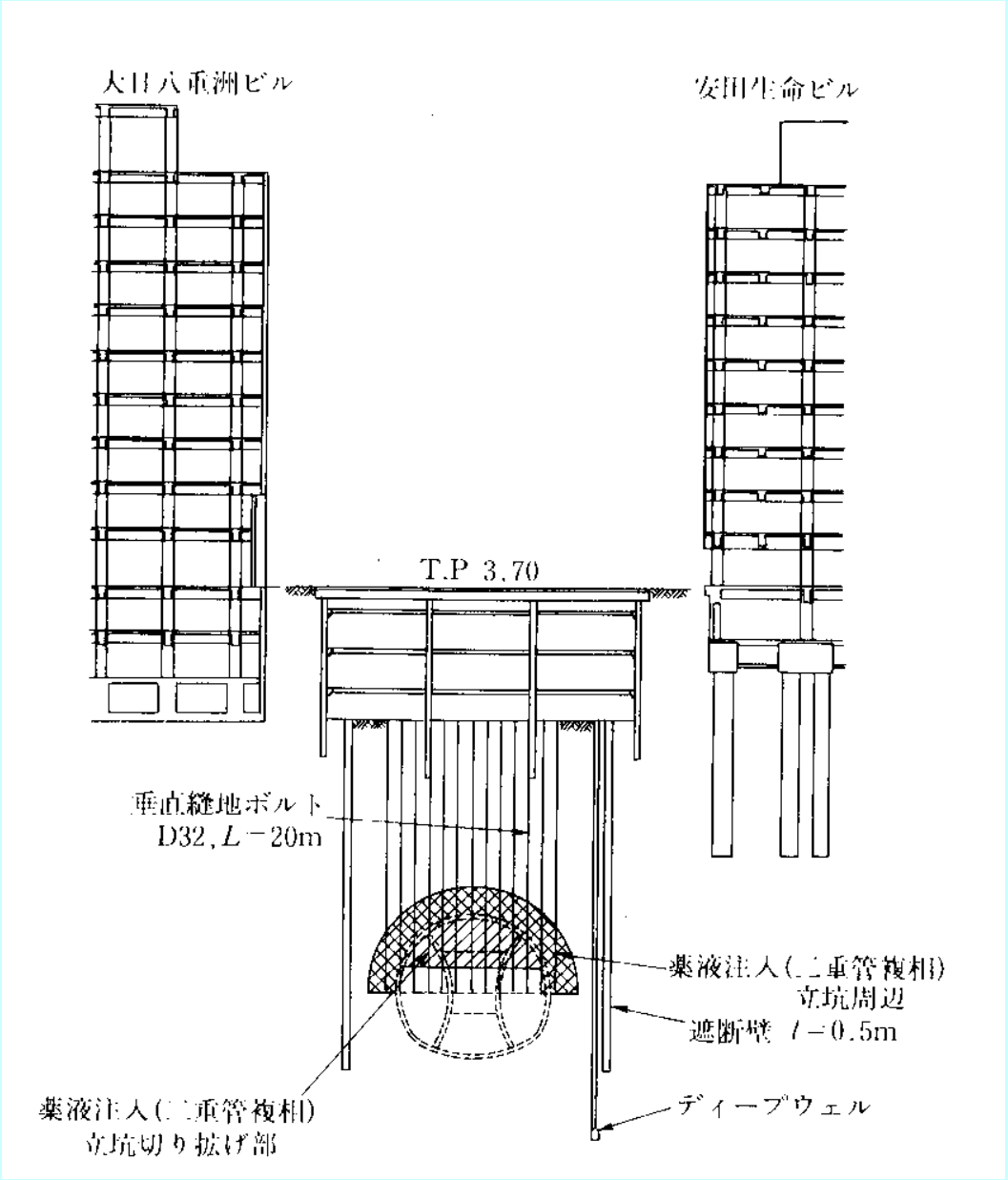
Location


京葉線東京地下駅
東京都庁
三菱銀行
東京ビル
中央郵便局
東京ステーション
都庁第2庁舎
首都高速4号線
鍛冶橋換気所
興銀ヤンマー
合同ビル
日本石油
大丸
八重洲
三井ビル
日本興業銀行
大和銀行
新八重洲
ロビ
NATMを採用した駅部トンネル

Standard cross section of the tunnel

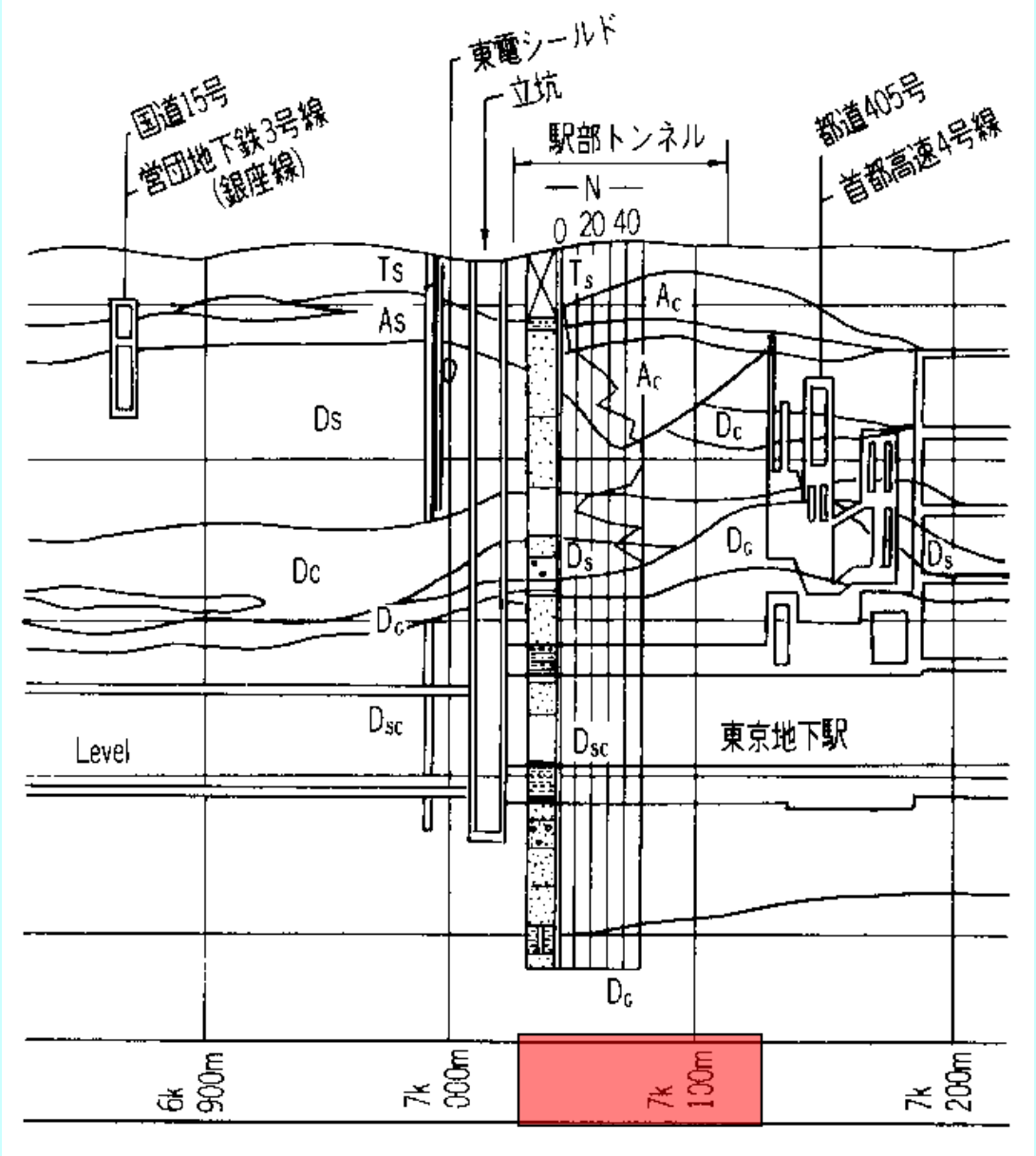


Standard cross section of the auxiliary method



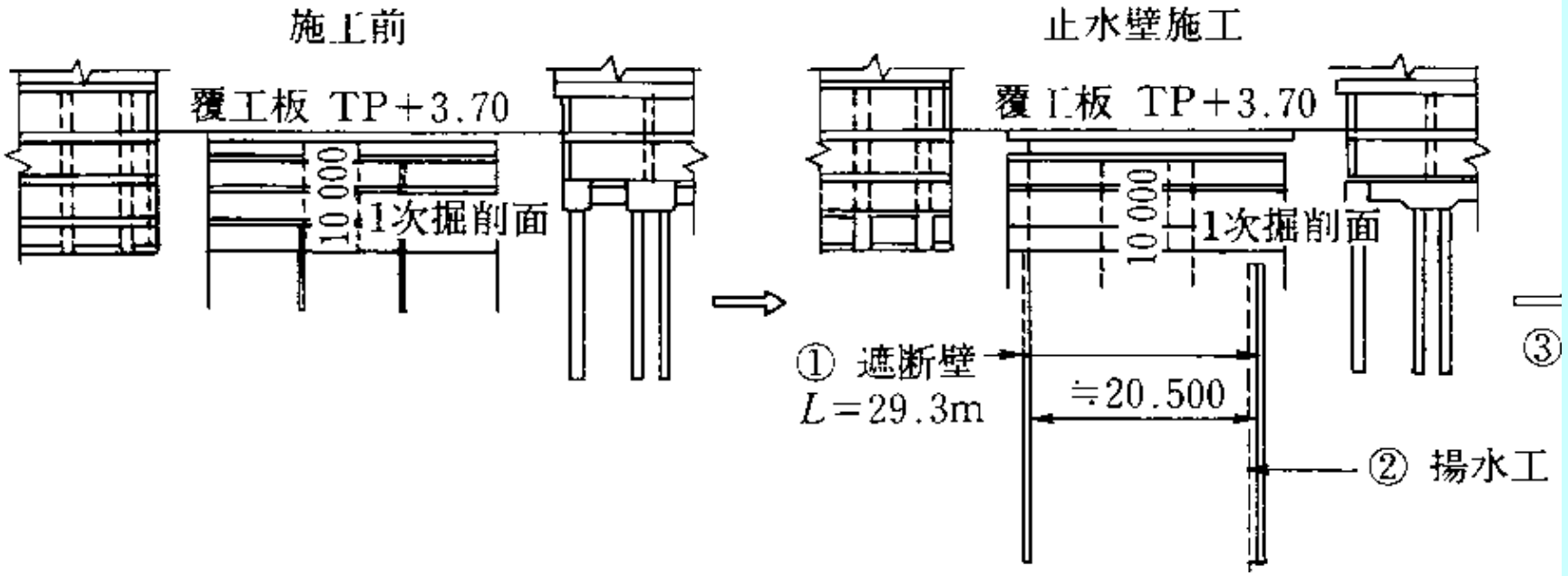

Meiji

Geological profile



Before construction

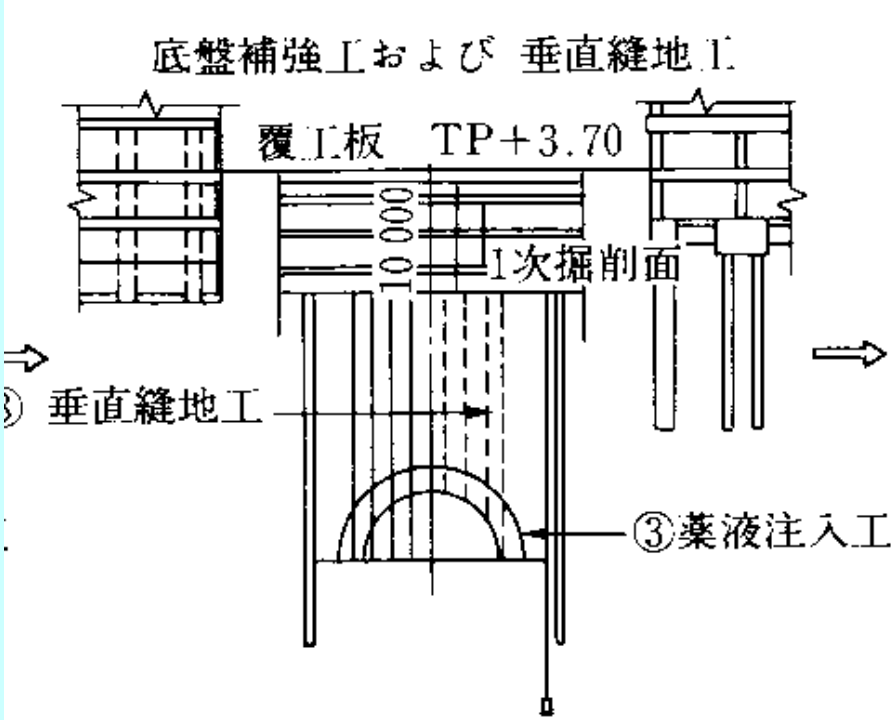
Construct the water cut-off wall (water isolation wall)

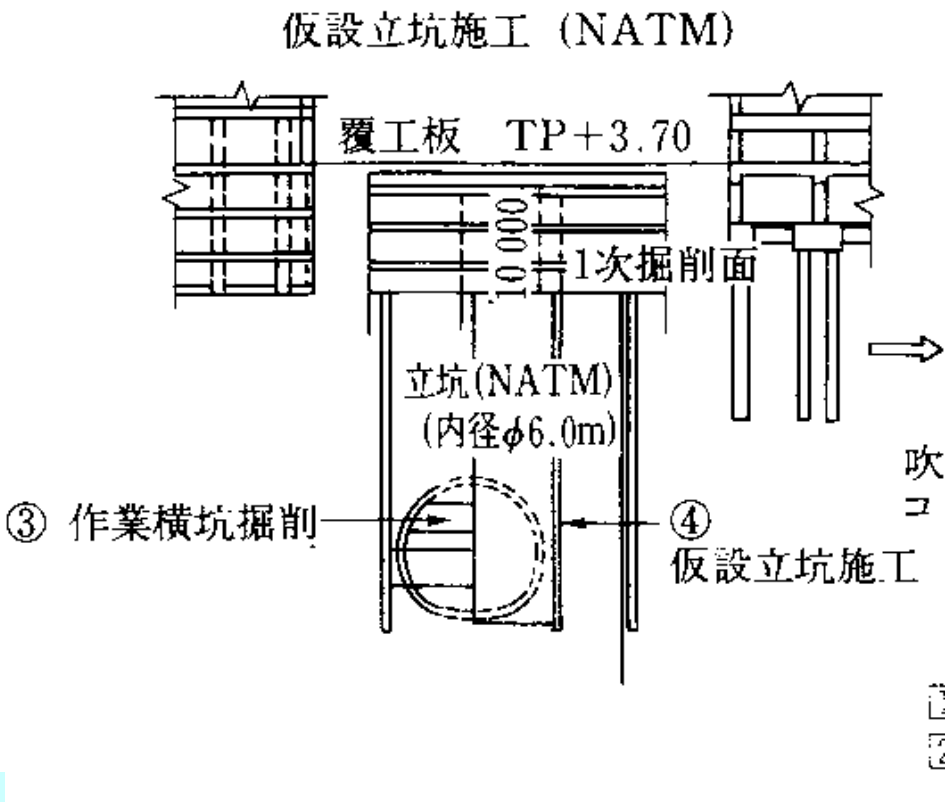


Base improvement.

Vertical pre-reinforcement.

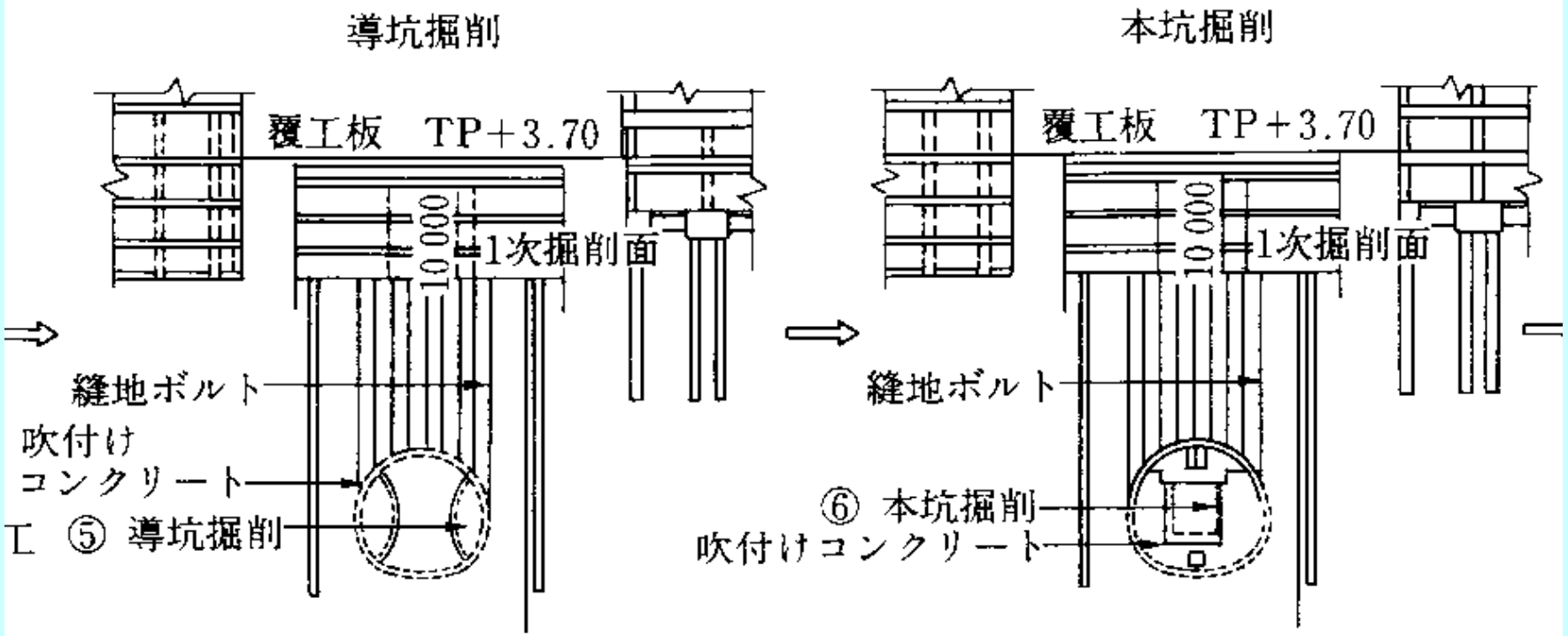
Constrict the temporary shaft by NATM.





Excavate side drifts

Excavate the main drift



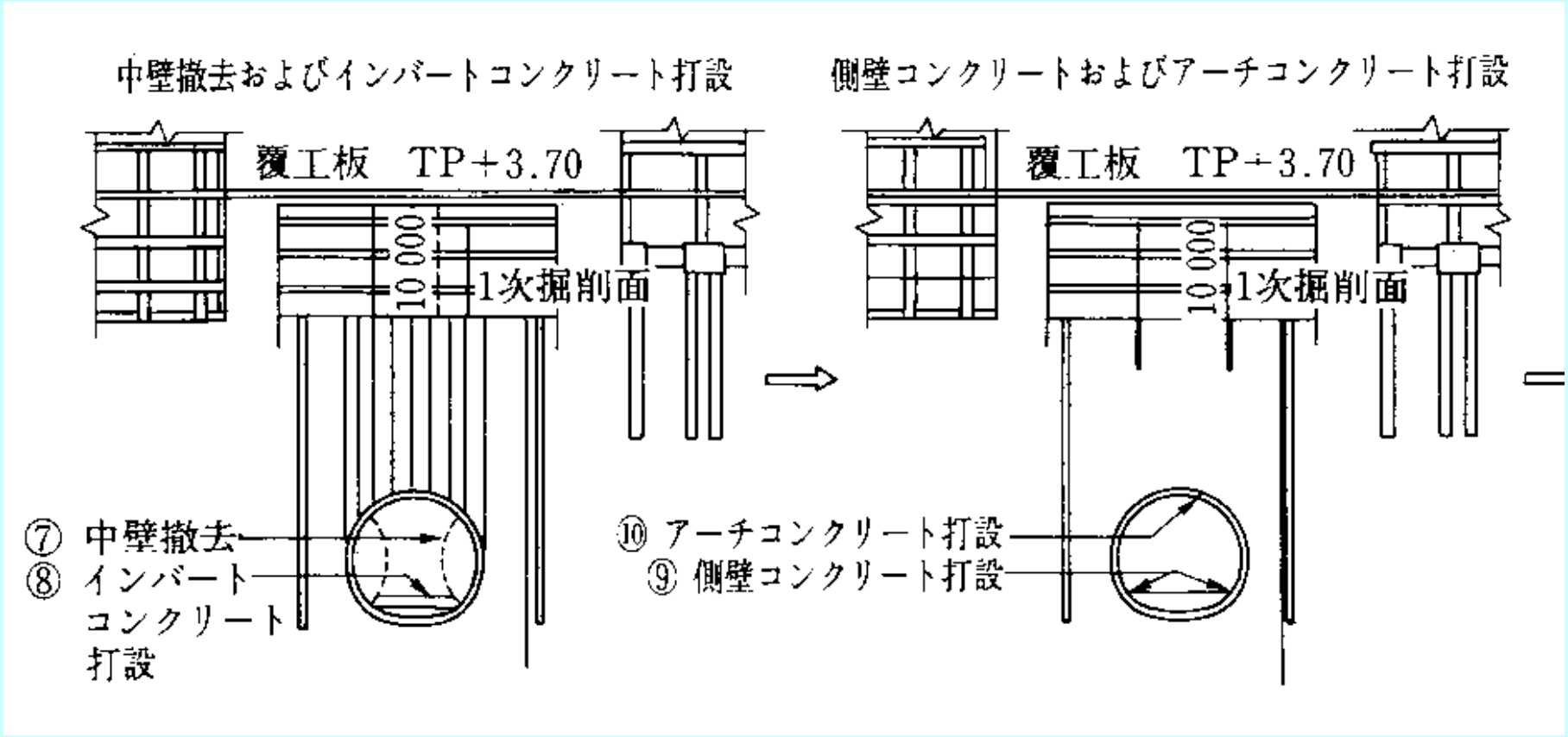
1 導坑上半掘削および吹付けコンクリート
2 導坑下半掘削および吹付けコンクリート

1 上半掘削および吹付けコンクリート
2 大背掘削および吹付けコンクリート
3 インバート掘削および吹付けコンクリート

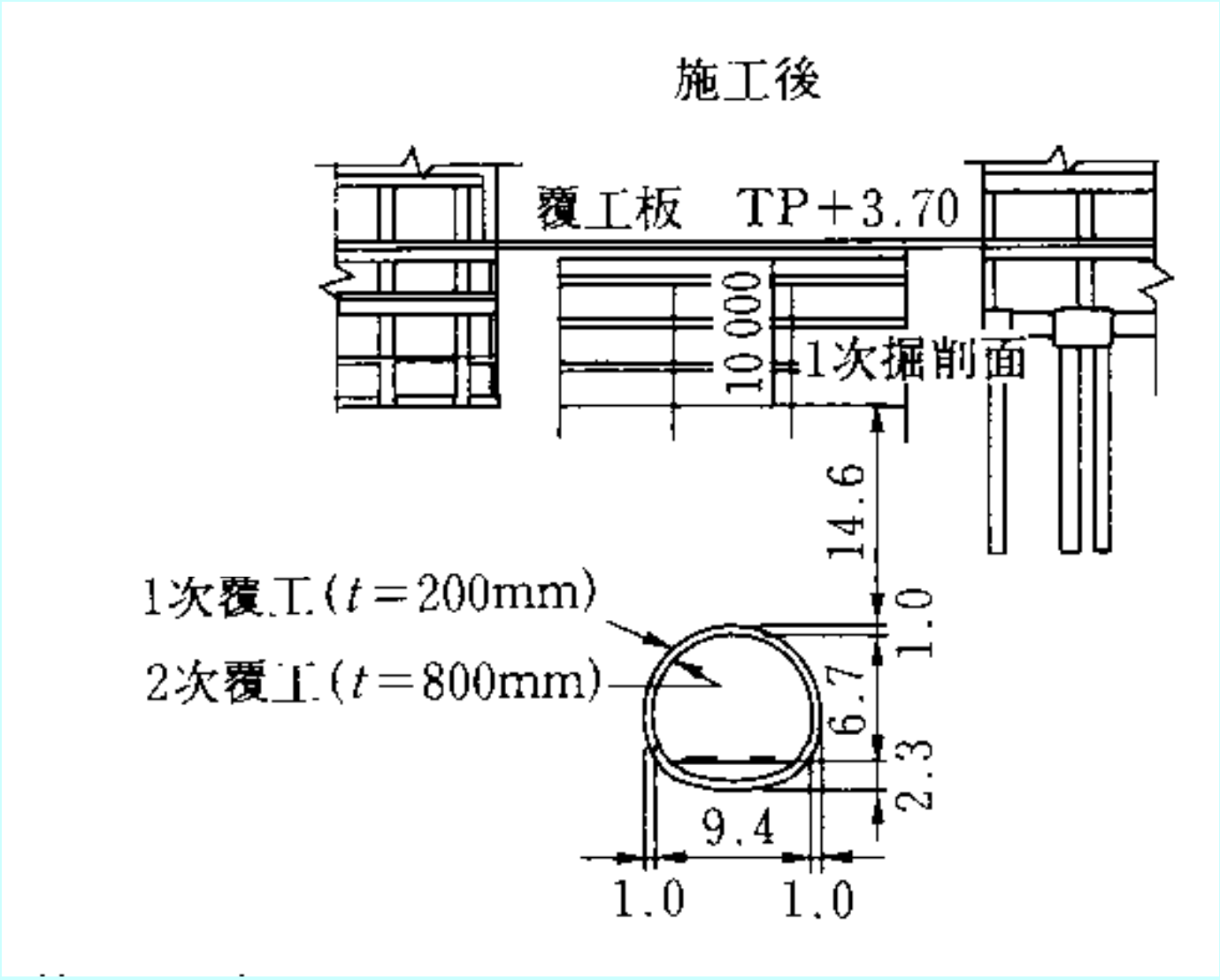
Remove temporary diaphragms.

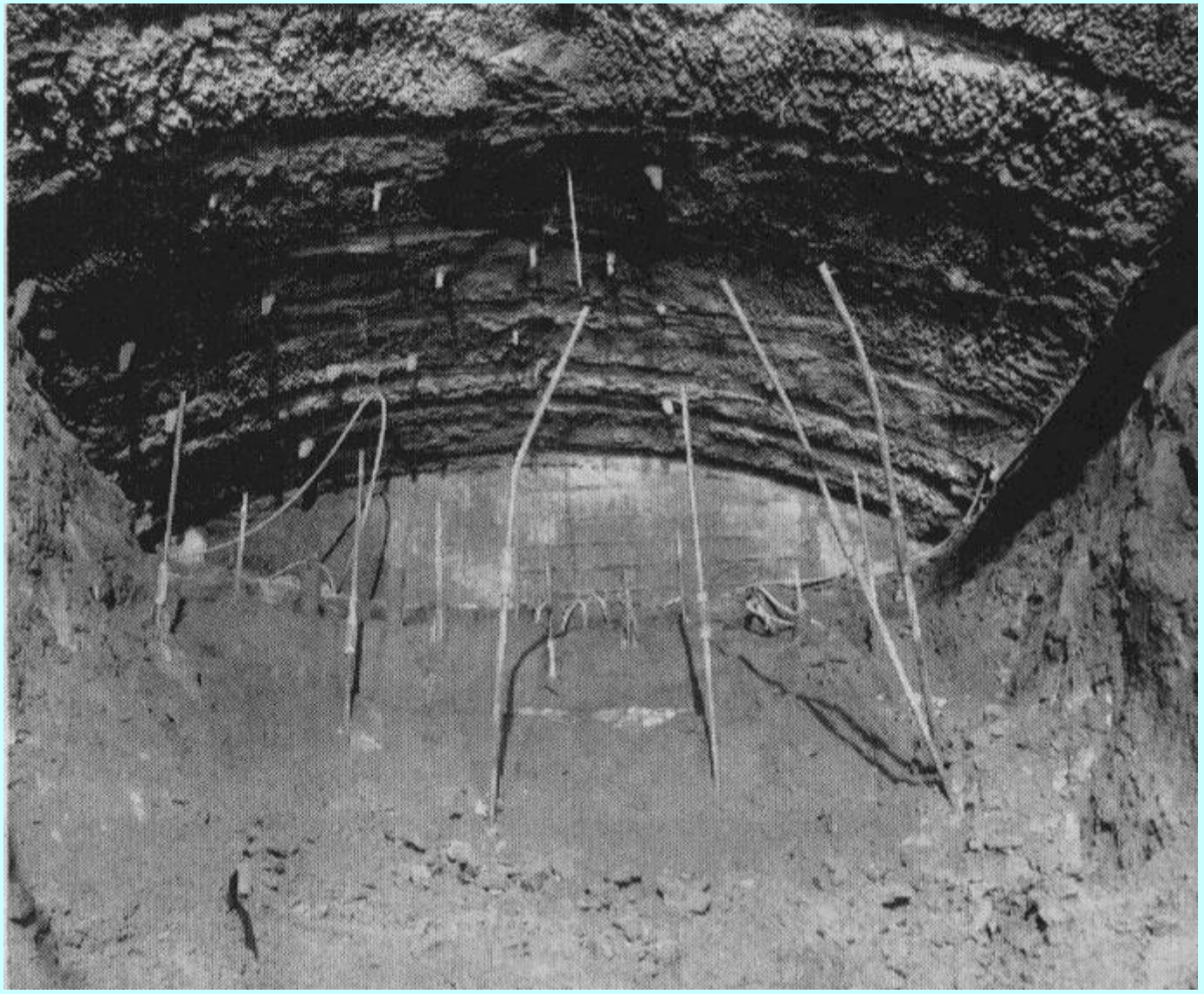
Placed invert concrete.

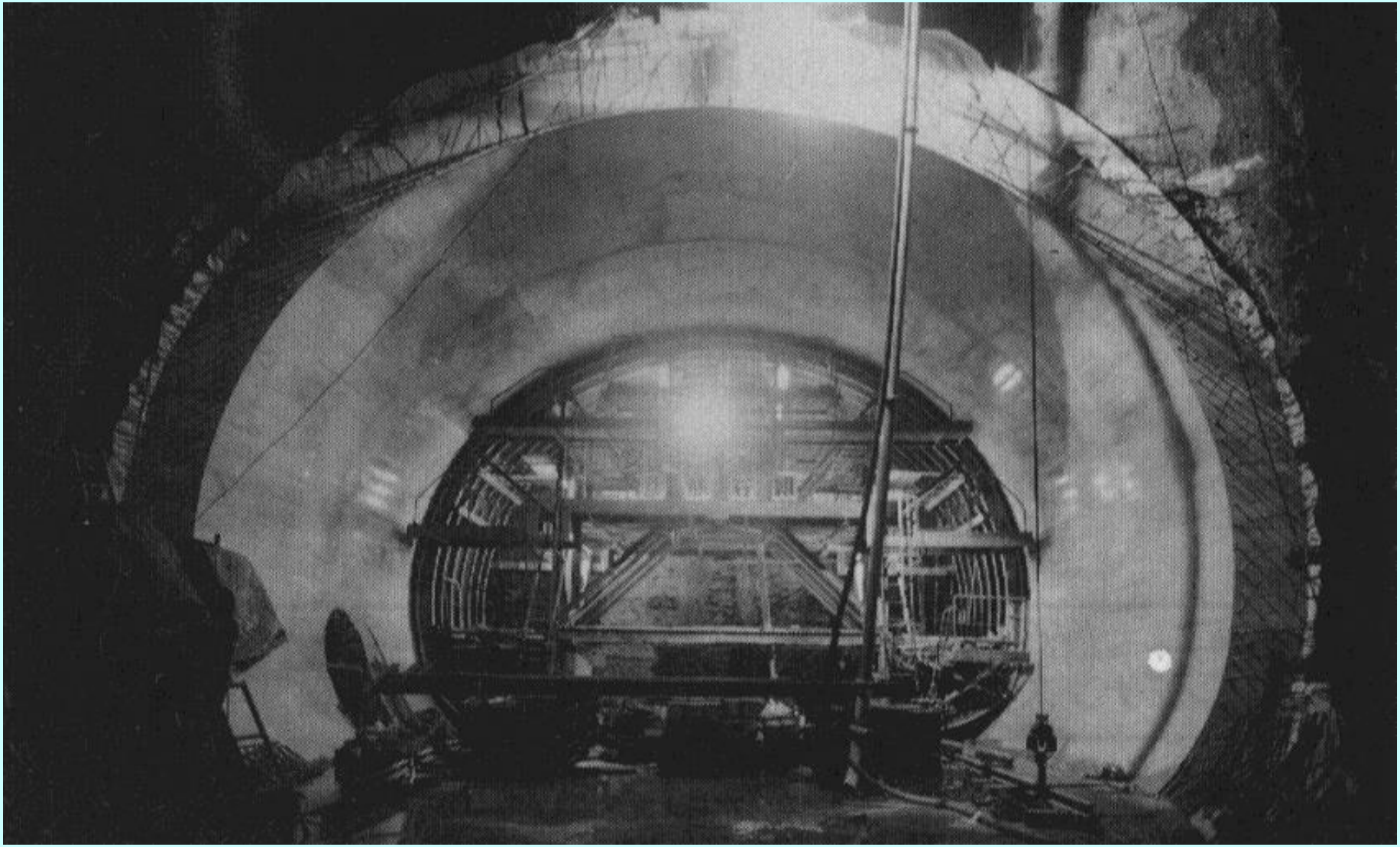
Placed side concrete
and arch concrete.



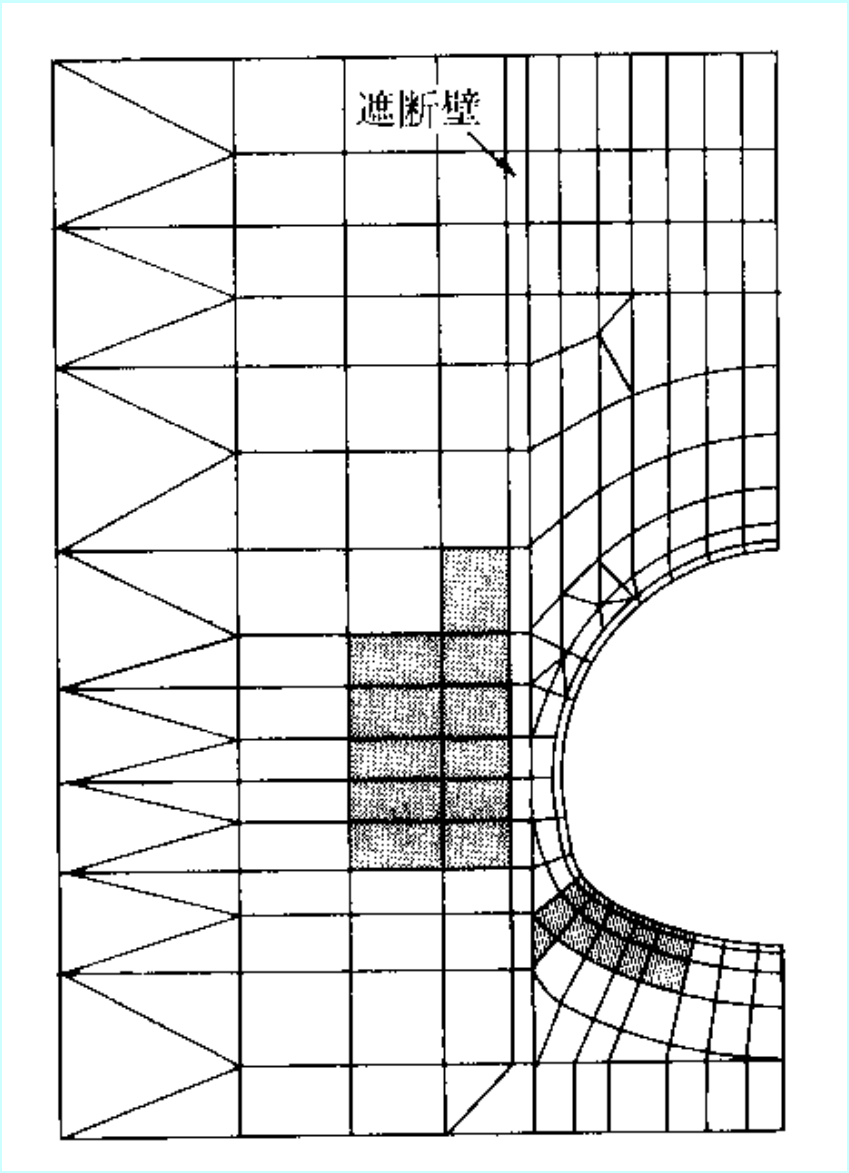
After construction.







Distribution of destroyed areas by FEM analysis



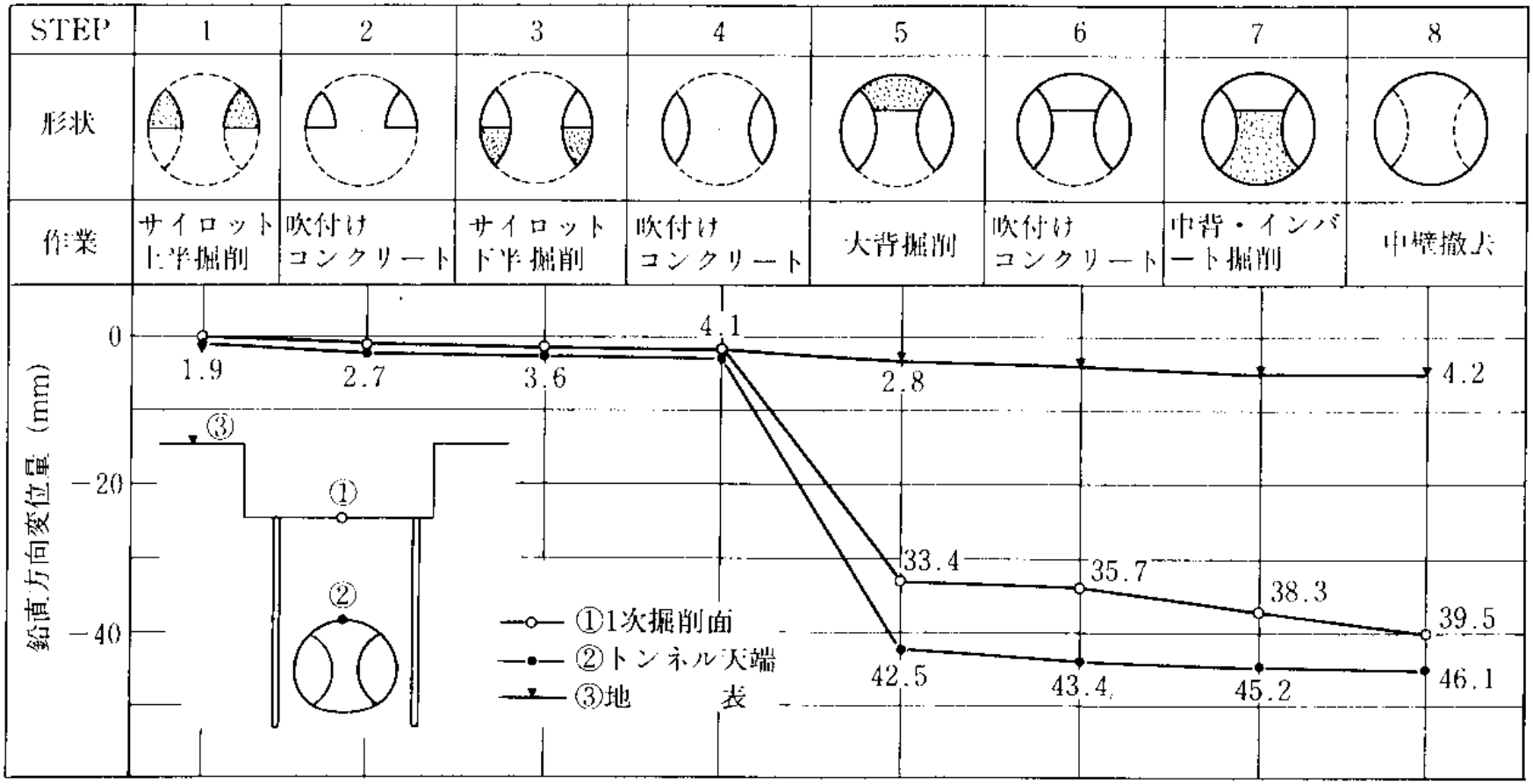
Prediction

Vertical pre-reinforcement bolt ⇨ **Bar element**

Ground and Water cut-off wall ⇨ **Joint element**

Load due to building ⇨ **10tf/m²**

Prediction of settlement by FEM analysis

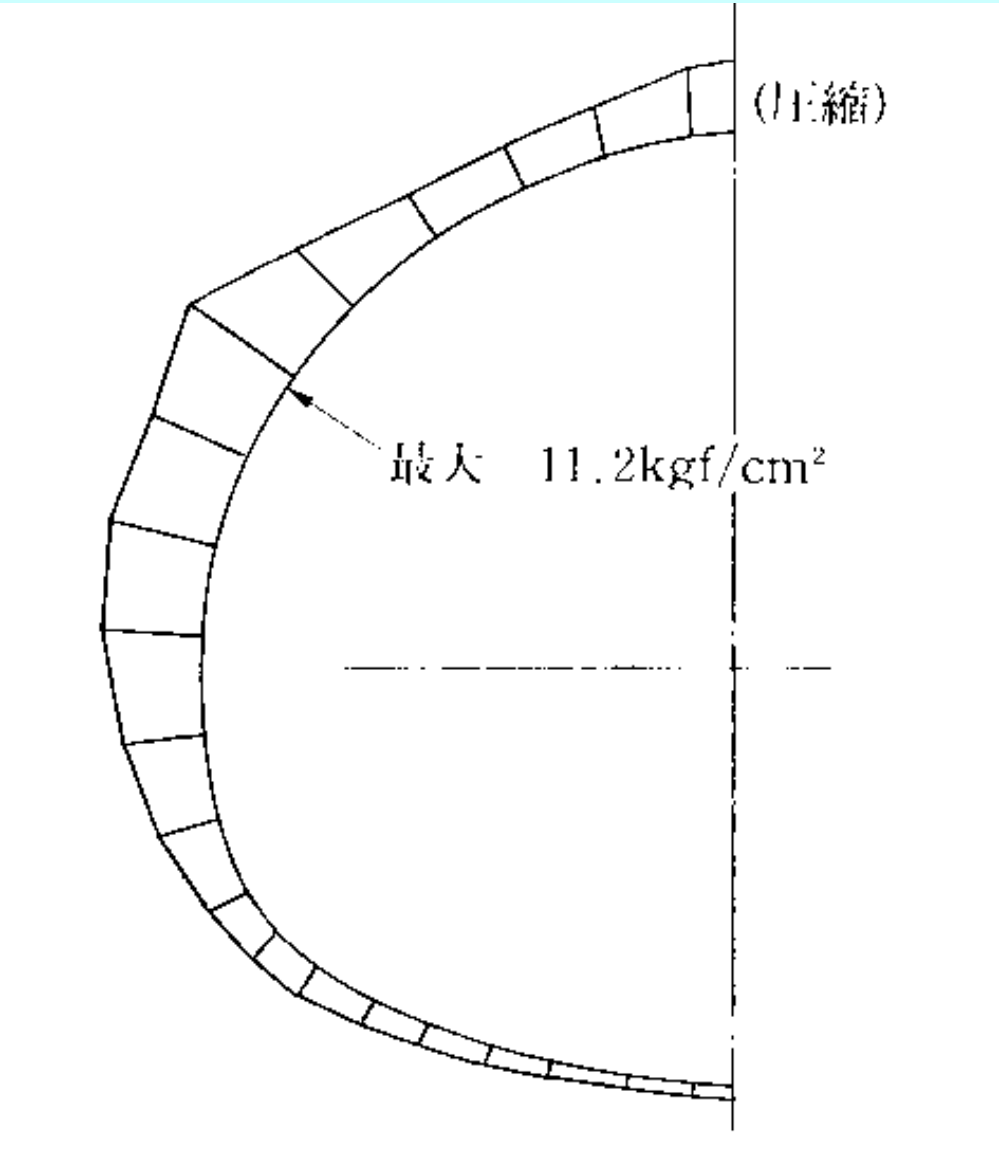


Release ratio

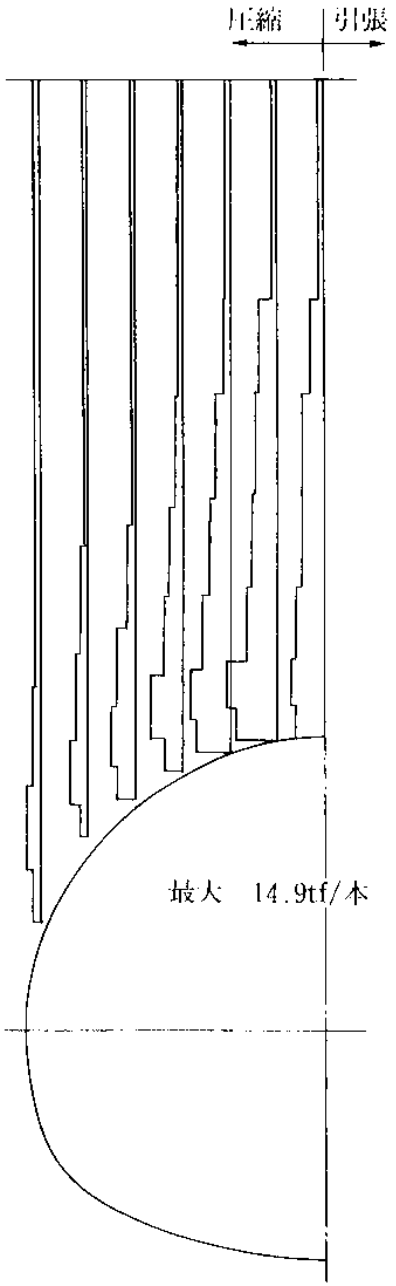
解放率

Excavation	**Excavation of top heading**	**Excavation of bench**
50%	**60%**	
Shotcrete	**Excavation of bench**	**100%**
50%	**40%**	

Distribution of stress of shotcrete



Distribution of axle forth of vertical pre-reinforcement bolts



Results of settlement

	Results of analysis by FEM	Actual measurement
Crown	46. 1mm	46. 1mm
First base	39. 5mm	0mm
Surface	4. 2mm	0mm

How do you make a tunnel face collapse?

My experience of model test

1. Pull a face board
2. Decrease a overburden
3. Increase height of a face
4. Increase gravity
5. Water
6. Excavation

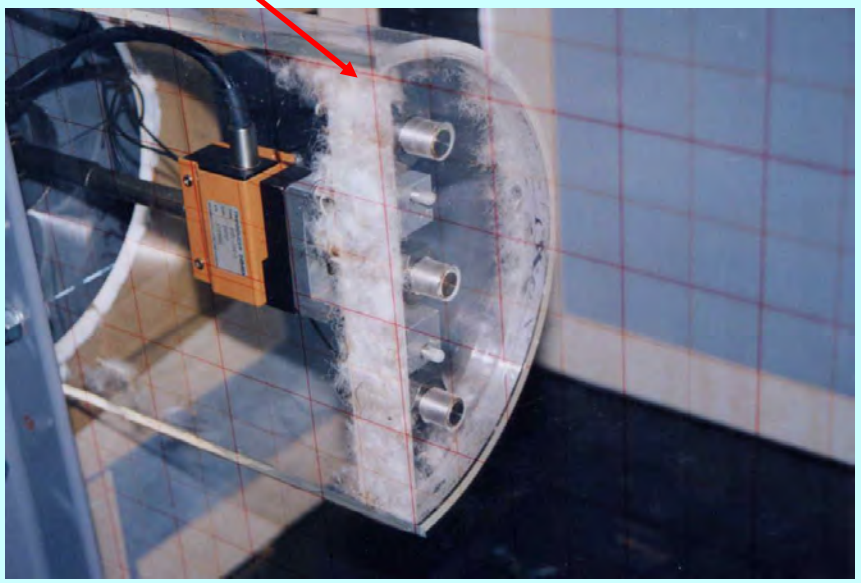
All of them are causes of face collapse!

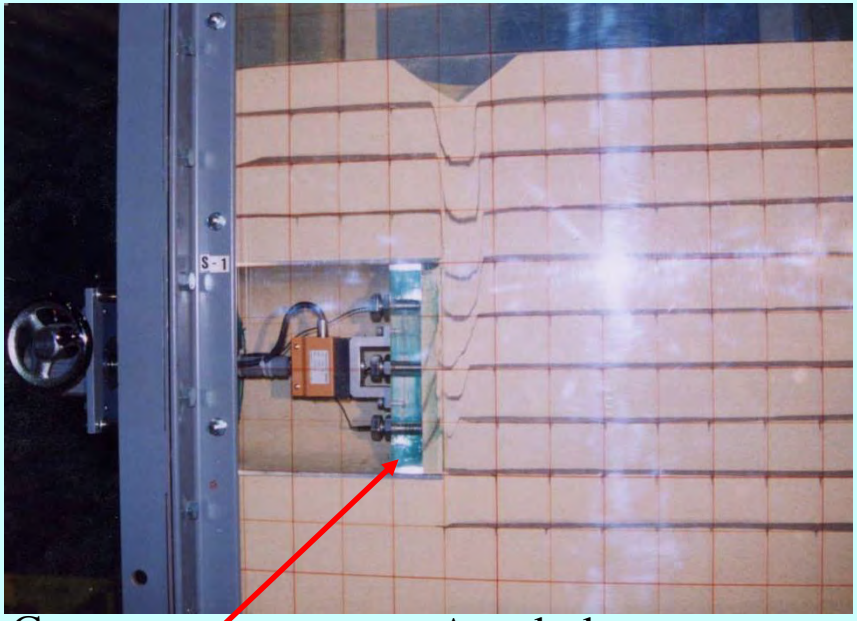
Pull a face board

Friction between an acryl plate and a face board

Collapse with static balance

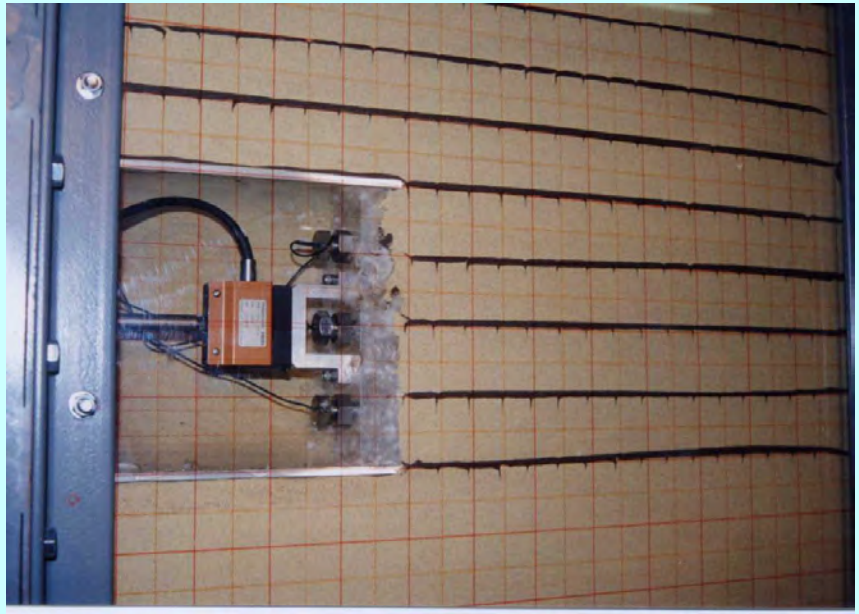
Feather





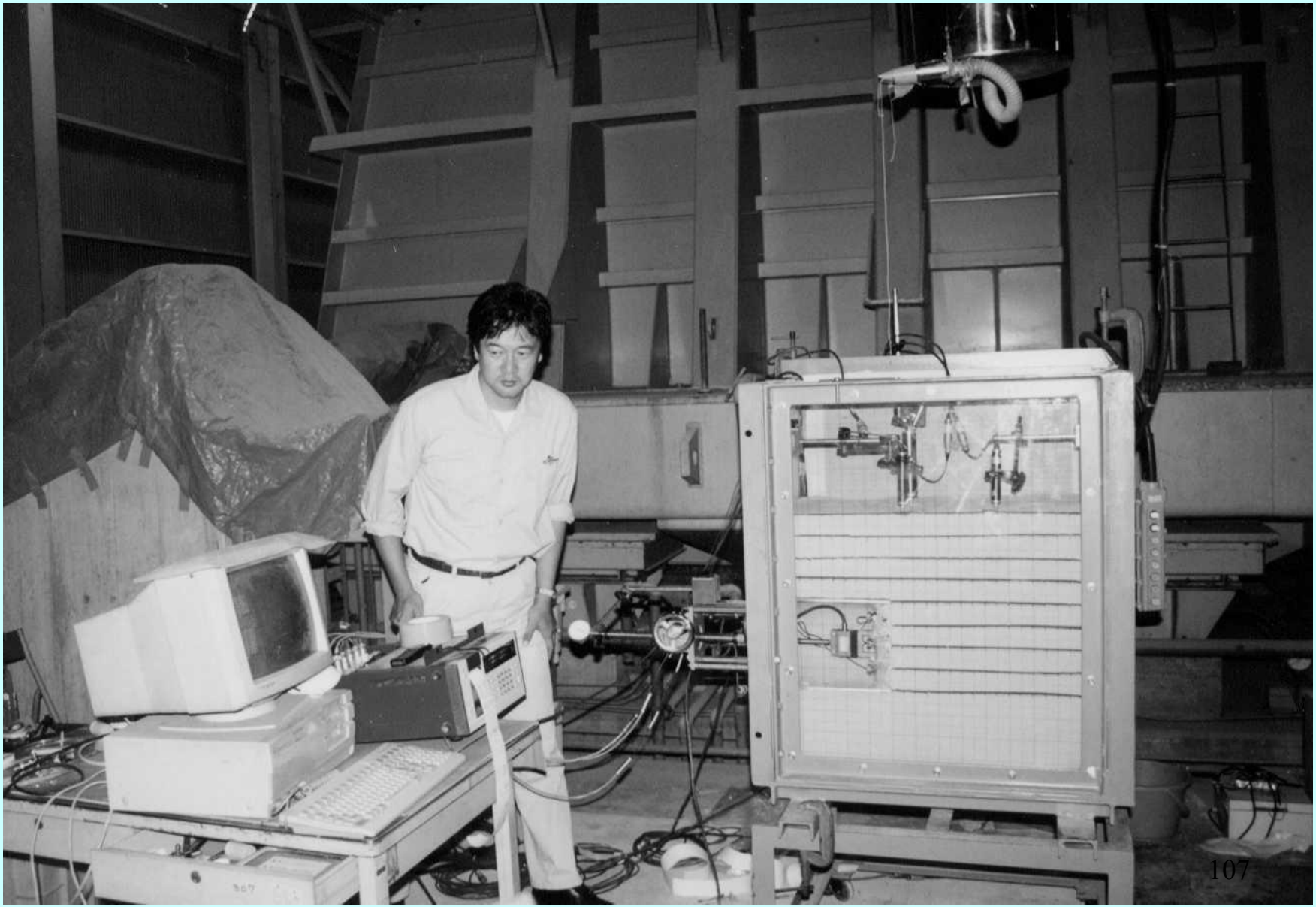
Grease

Acryl plate

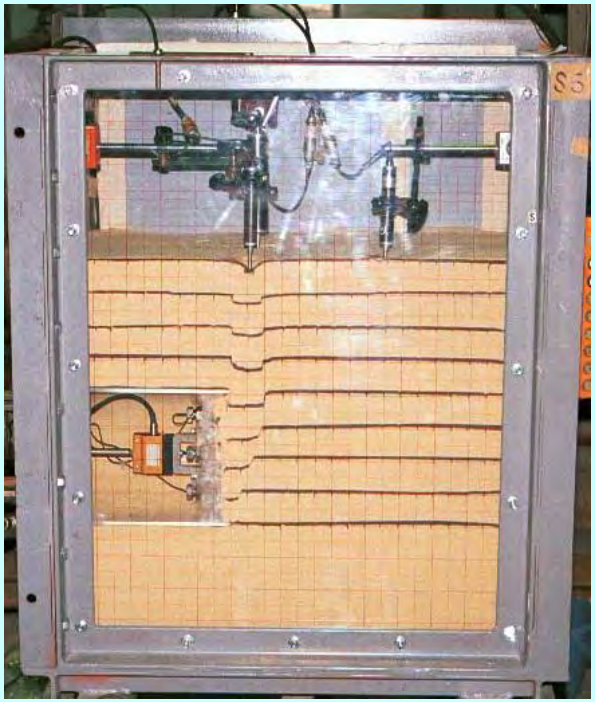


Hard glass board

Model experiments

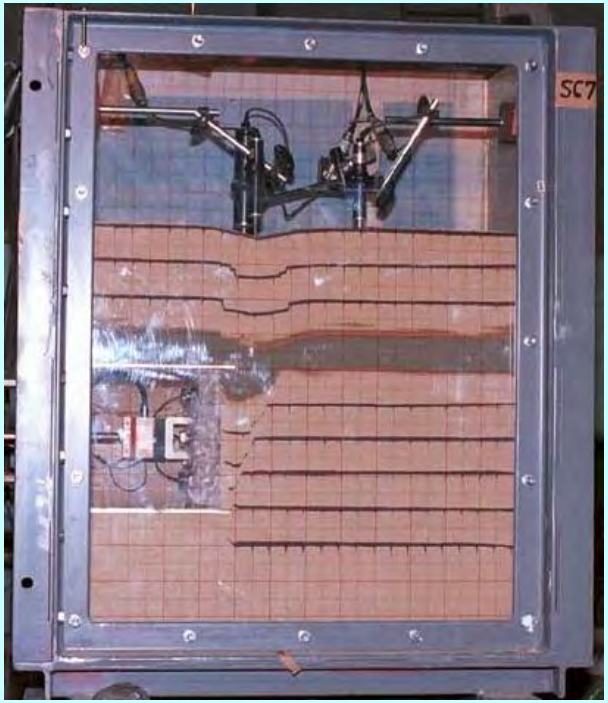


Face collapse

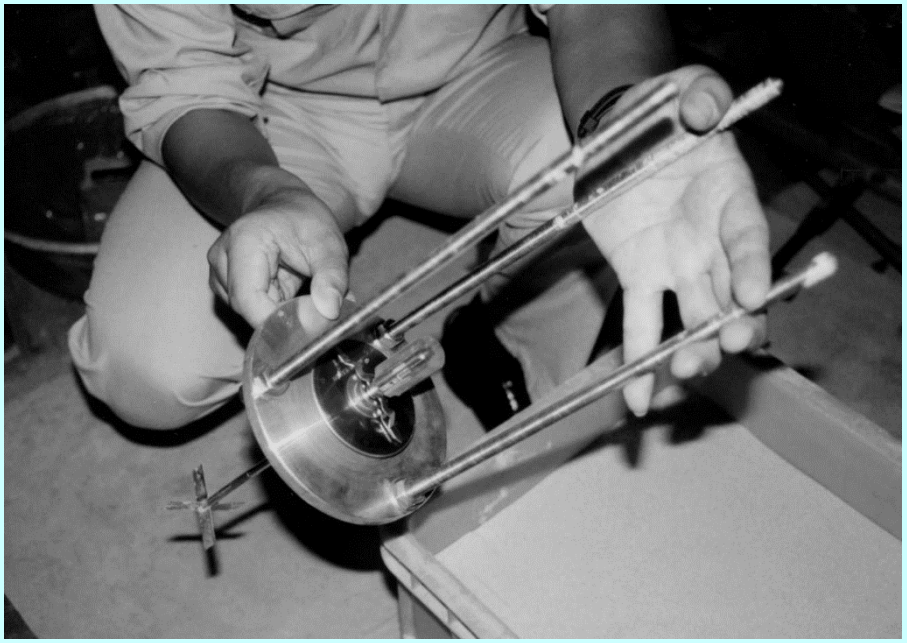


Sandy ground without a clay layer.

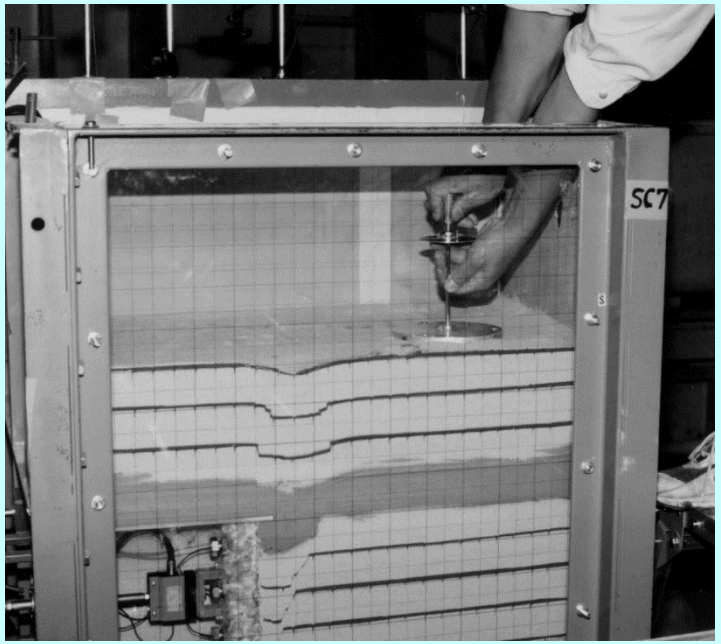
Sandy ground with a clay layer at middle of the tunnel.



Sandy ground with a clay layer at crown.



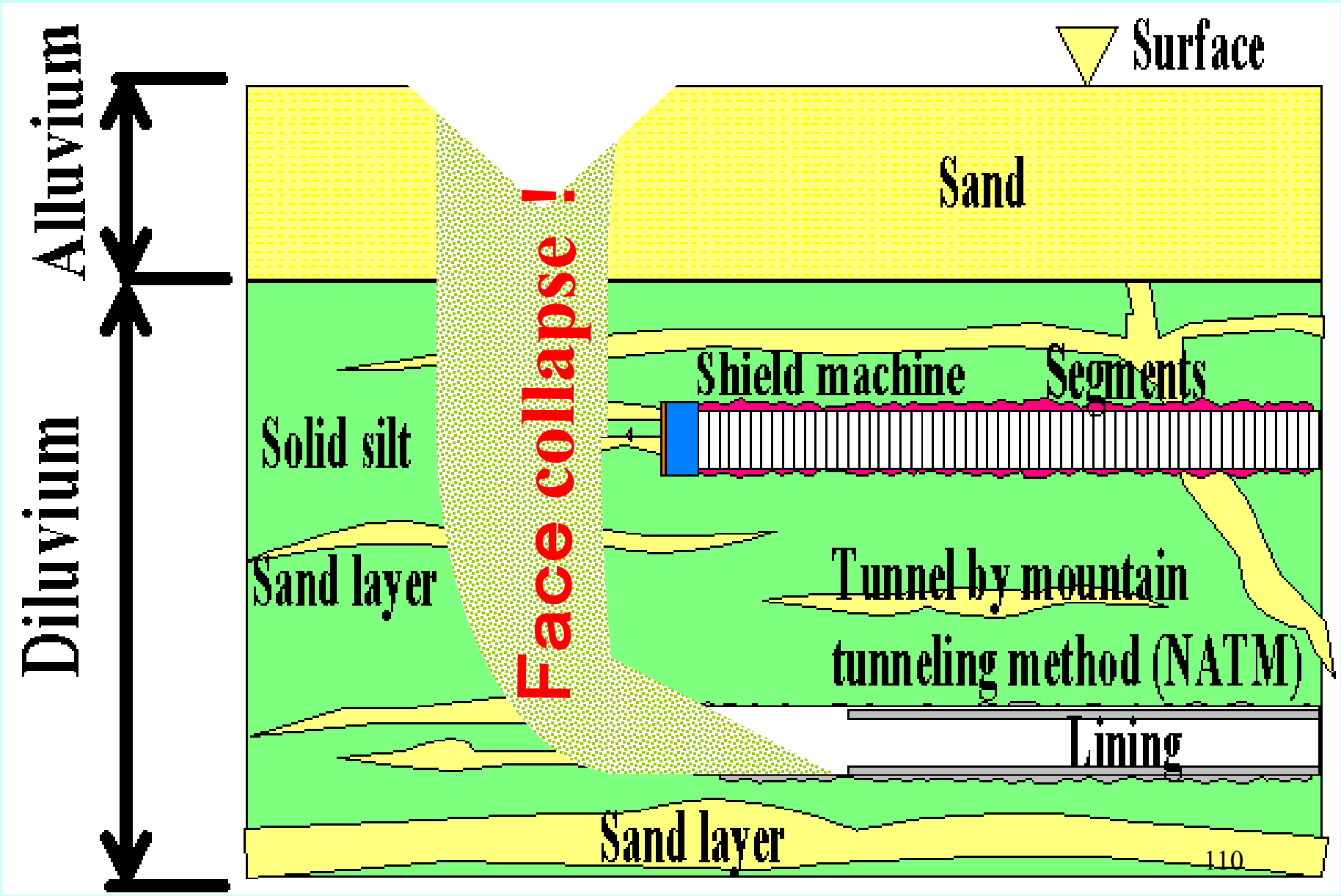
Mini vane shear test



State of the vane shear test

Vane shear test

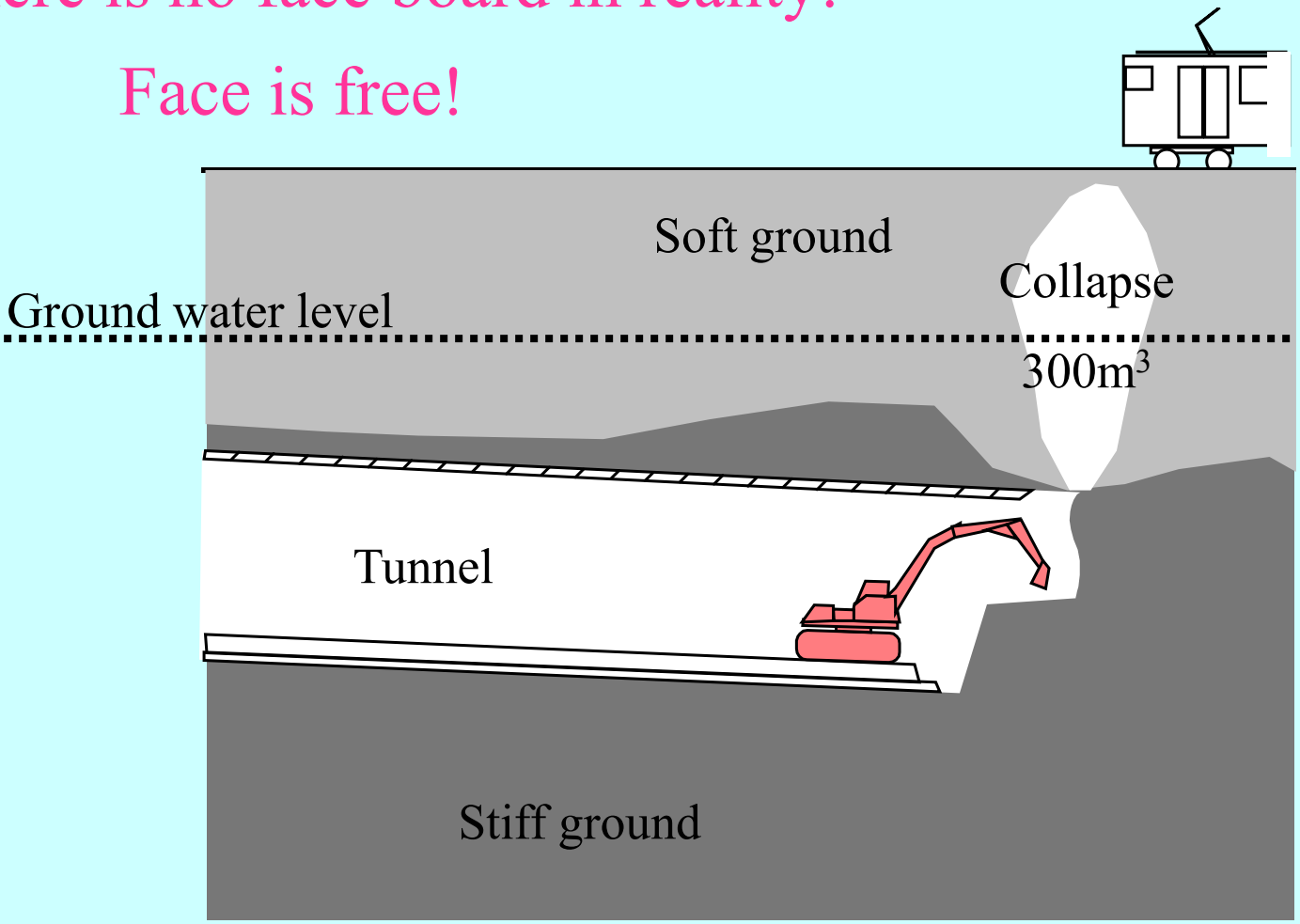
Purpose･Background



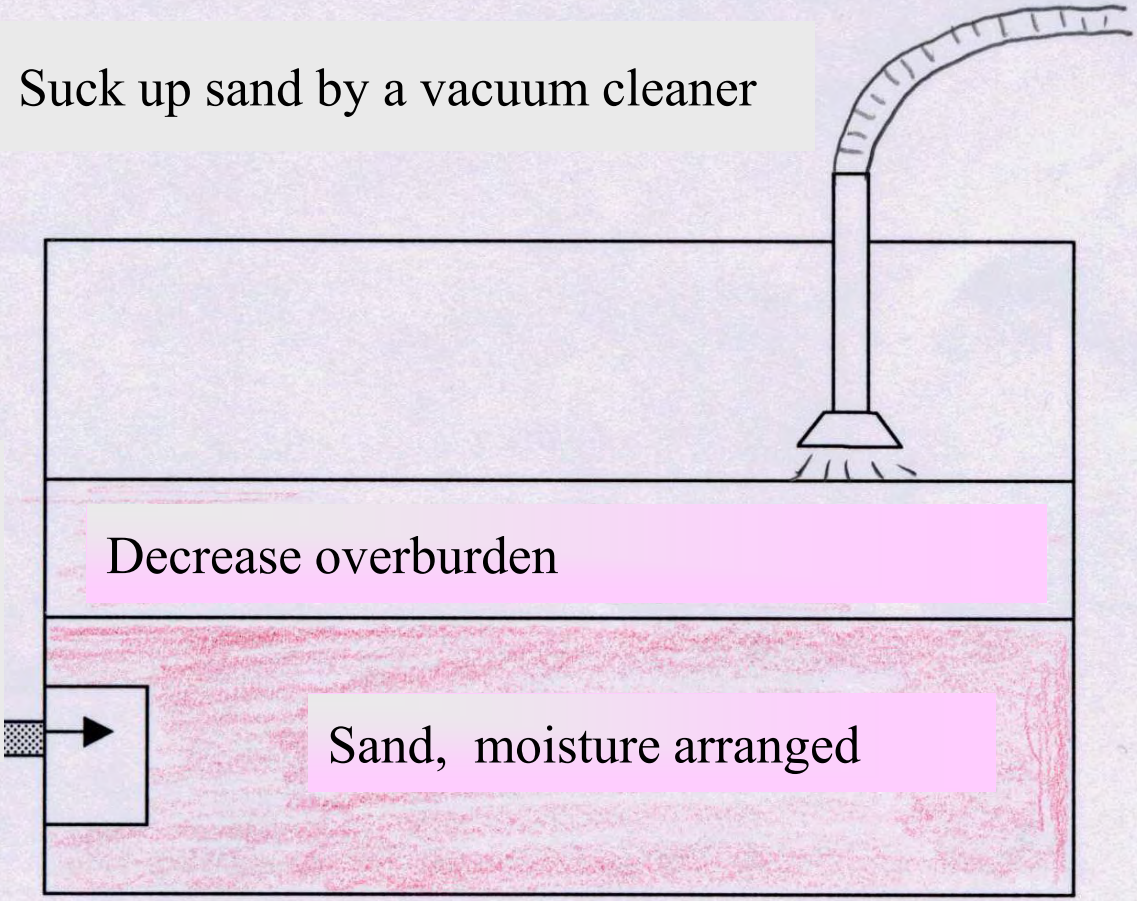
A real example of face collapse

There is no face board in reality!

Face is free!

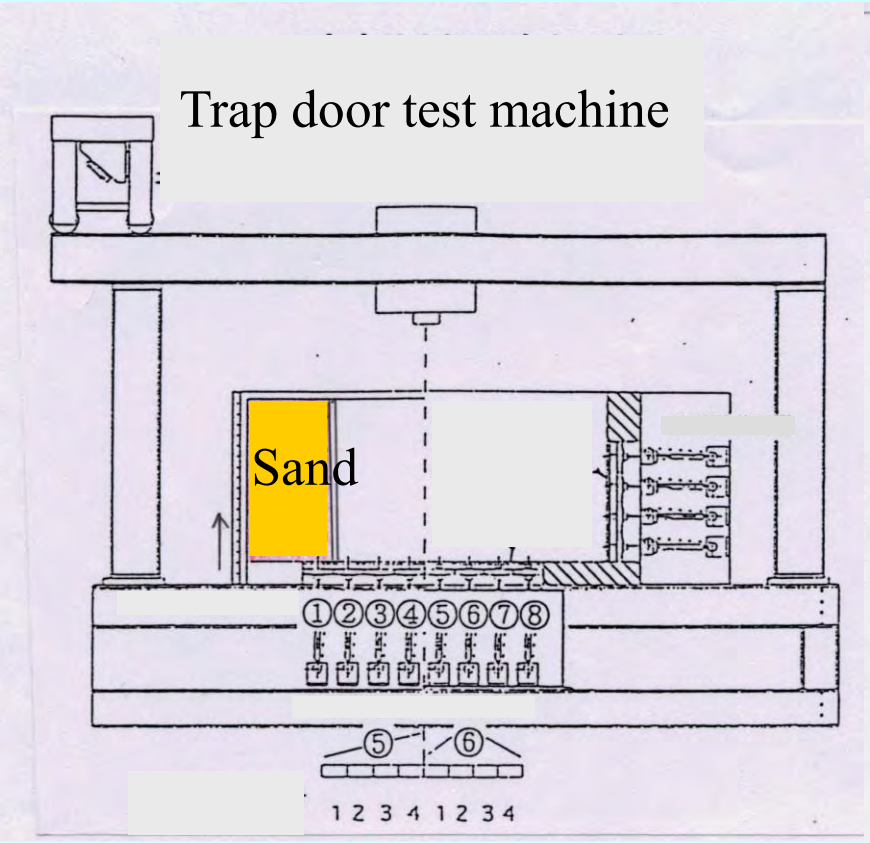


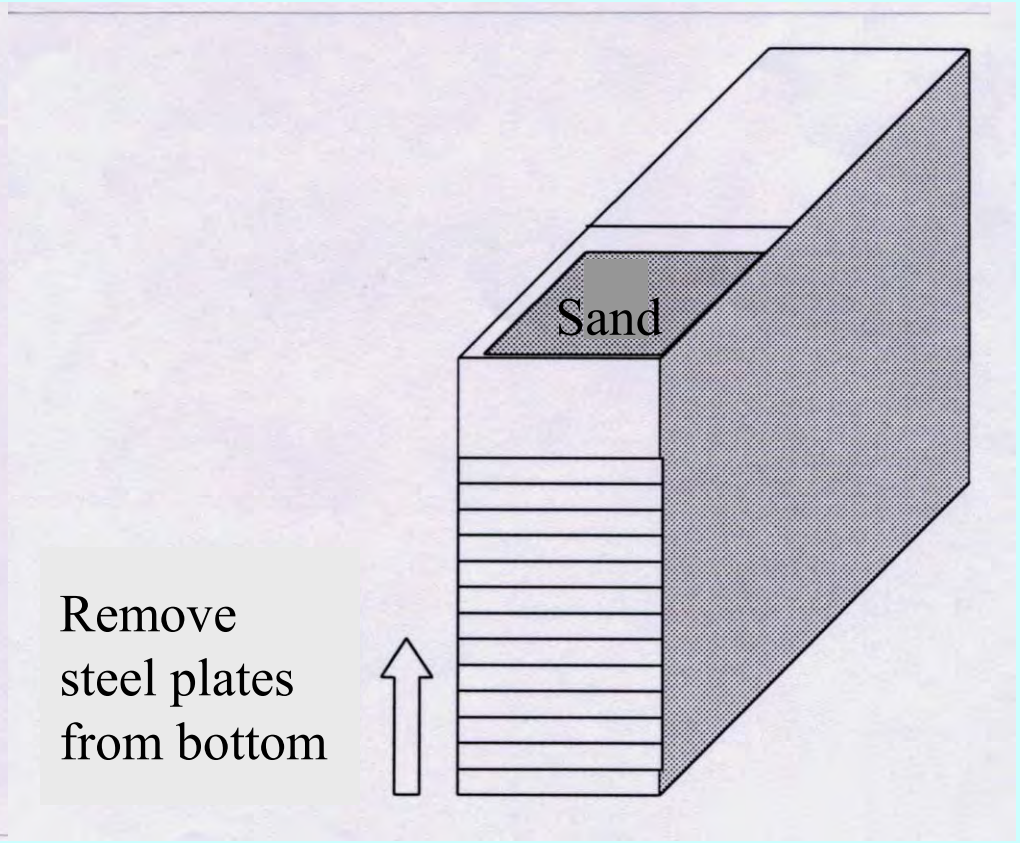
Decrease overburden



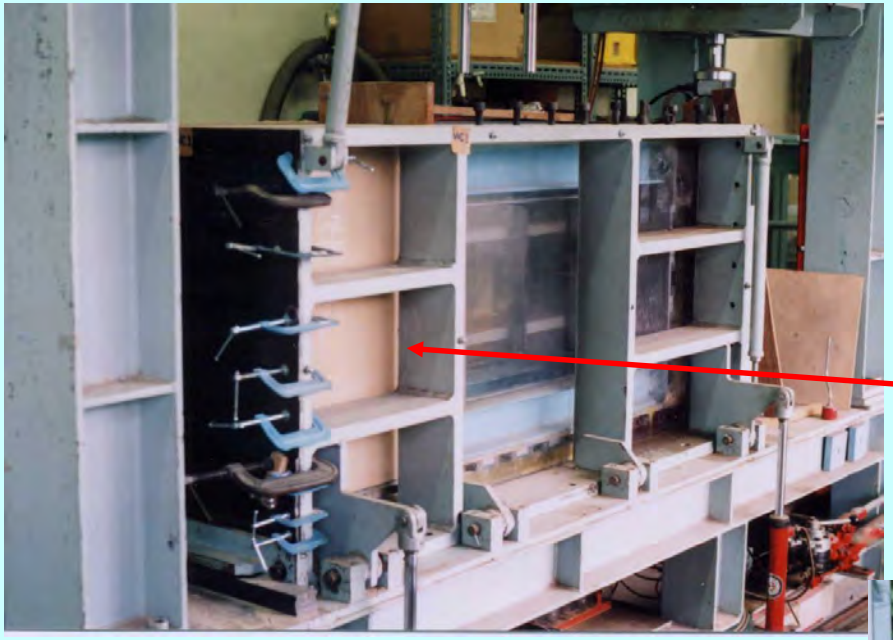
It is difficult to investigate relation between apparent cohesion and water content.

Increase height of a face



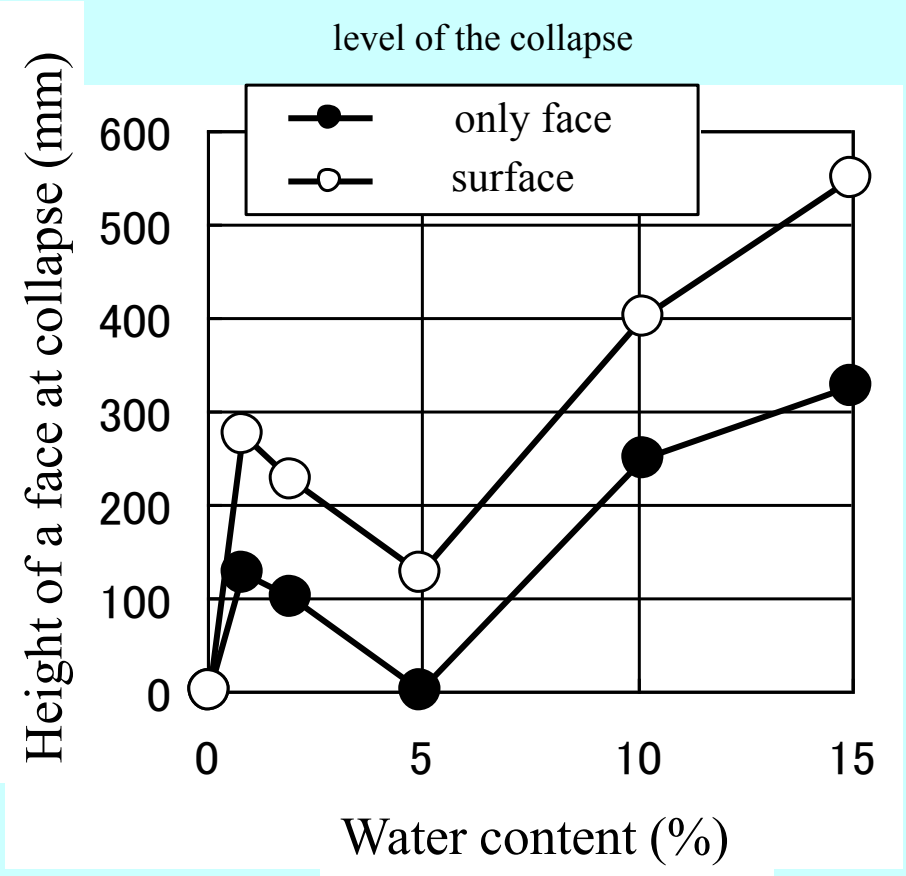


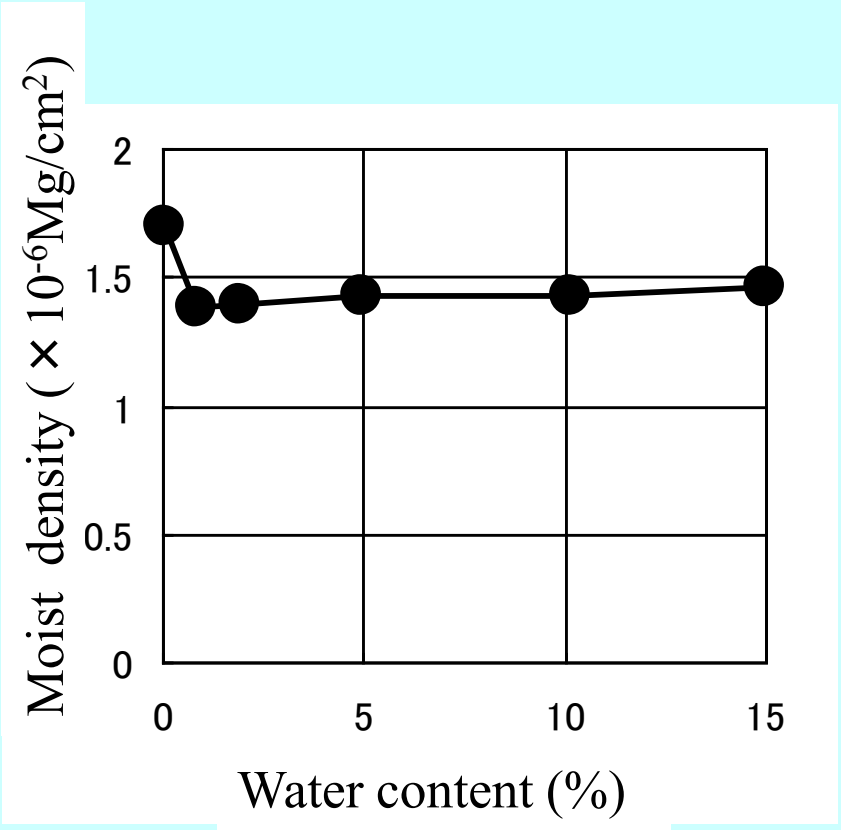
Increase height of a face



A part of trap door test machine

Remove steel plates from bottom



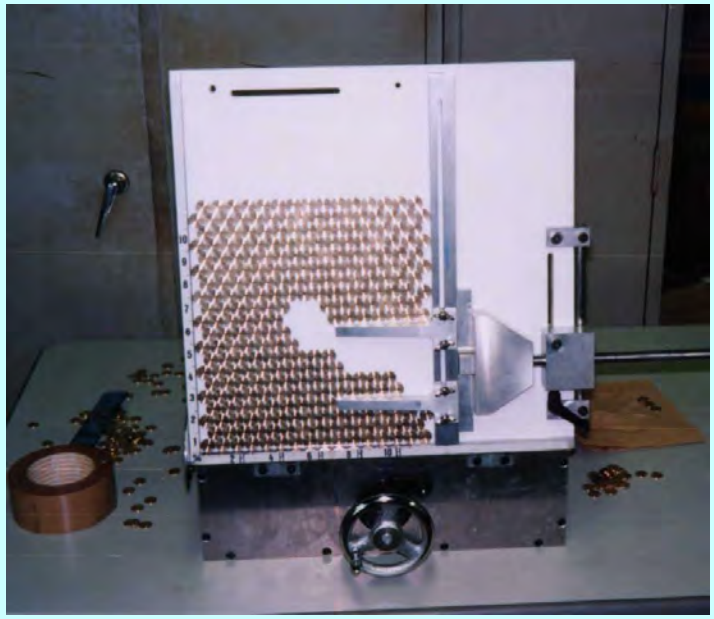


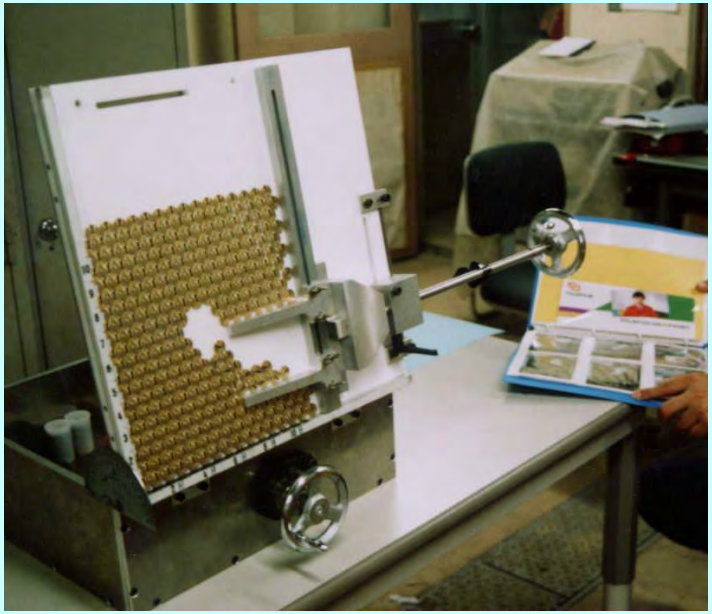
Relation between height of self-stand and water content

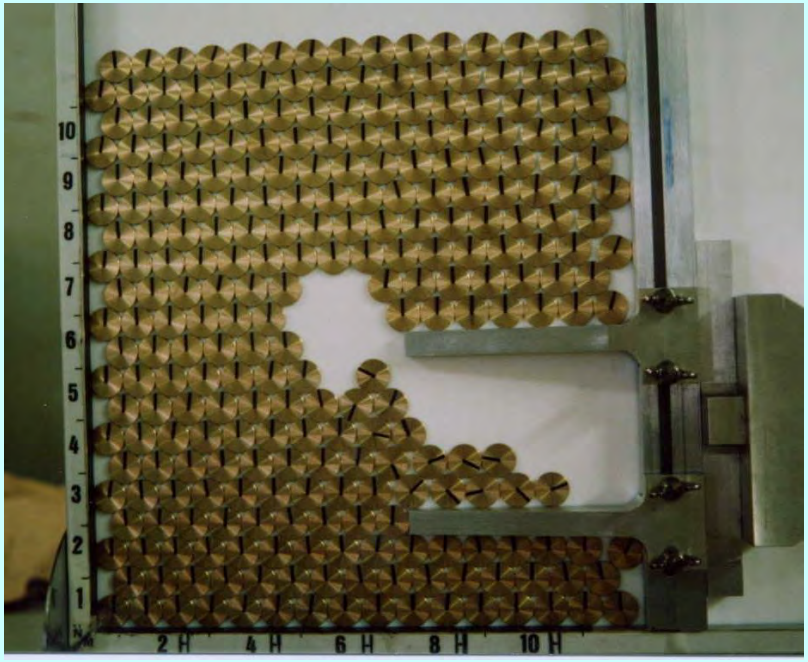
Relation between moist density and water content

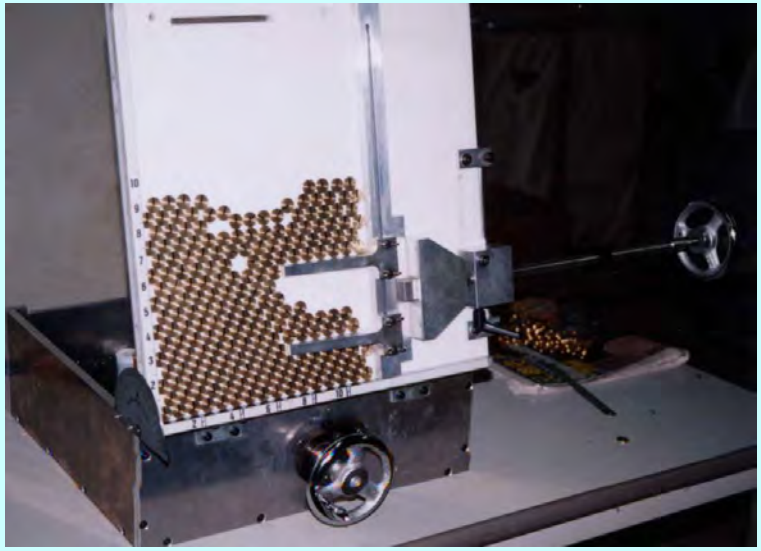
Apparent cohesion can make self-standing face of over 50 cm height.

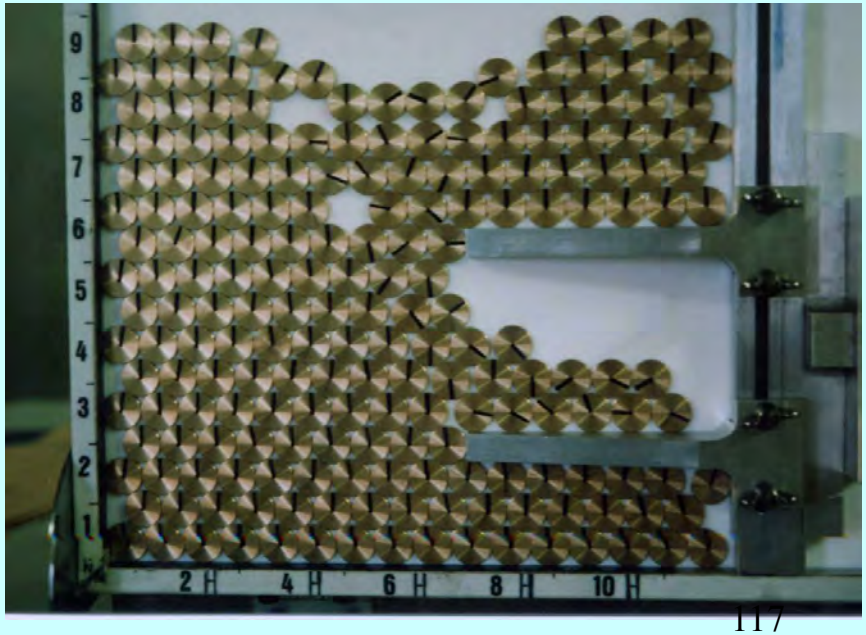
Increase gravity






10
9
8
7
6
5
4
3
2
1
2 H
4 H
6 H
8 H
10 H




9
8
7
6
5
4
3
2
1
2 H
4 H
6 H
8 H
10 H

1. First collapse (Inclination angle is About 30degree),
   Second collapse(About 60degree)

2. A rotated coin always down and collapse in a little later.

3. Lattice arrangement never collapse.

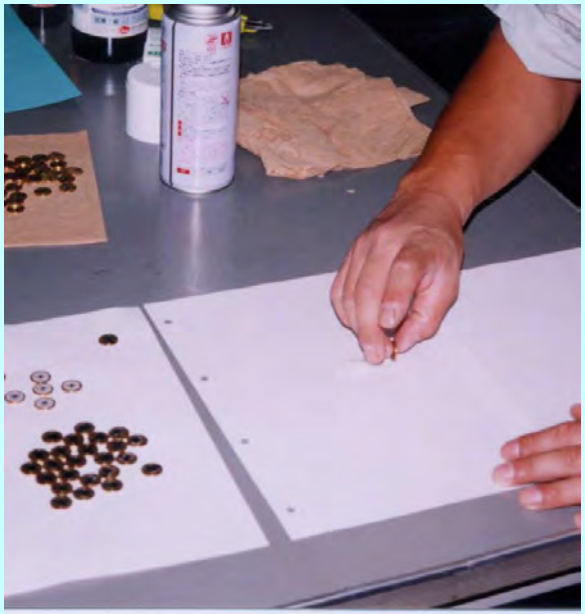
4. When Diameter of coin become large against it of tunnel, the tunnel collapse easily.

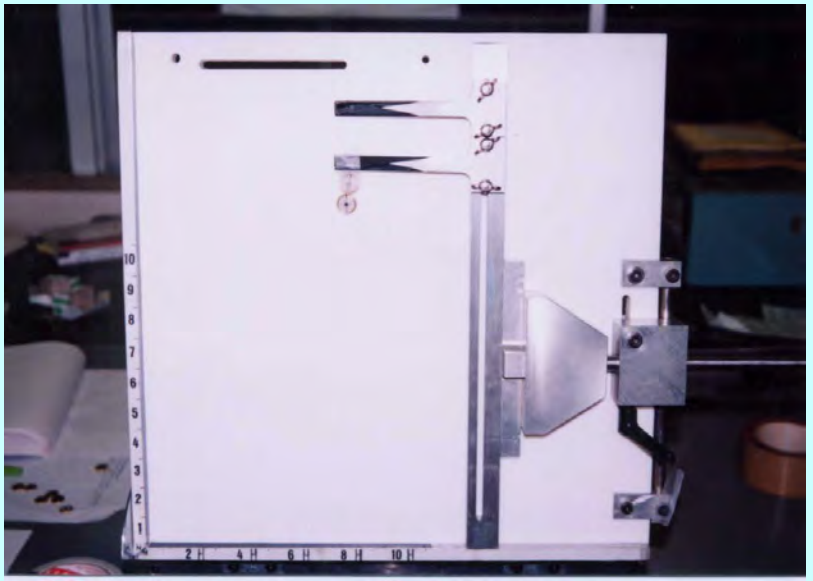
5. When overburden is large, huge collapse which reaches to ground surface doesn’t occur.

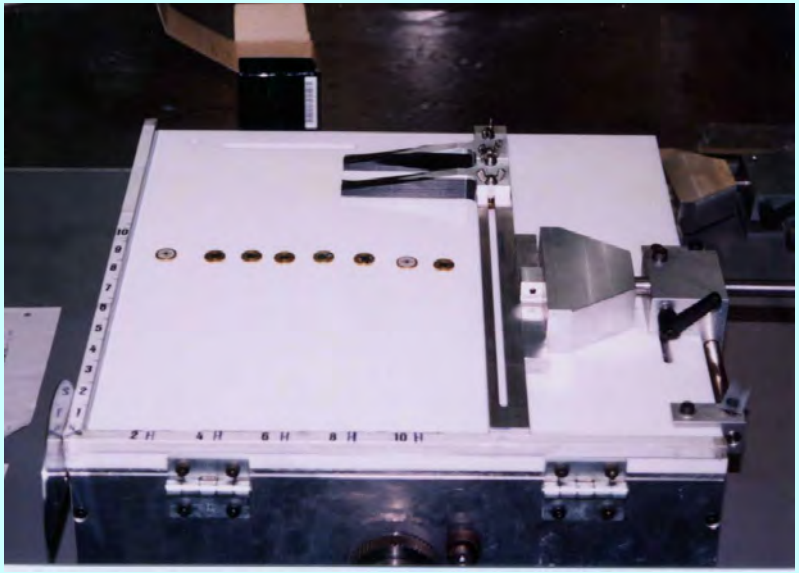
6. There are some pattern of slip lines.

Make a clay layer

Spray paste

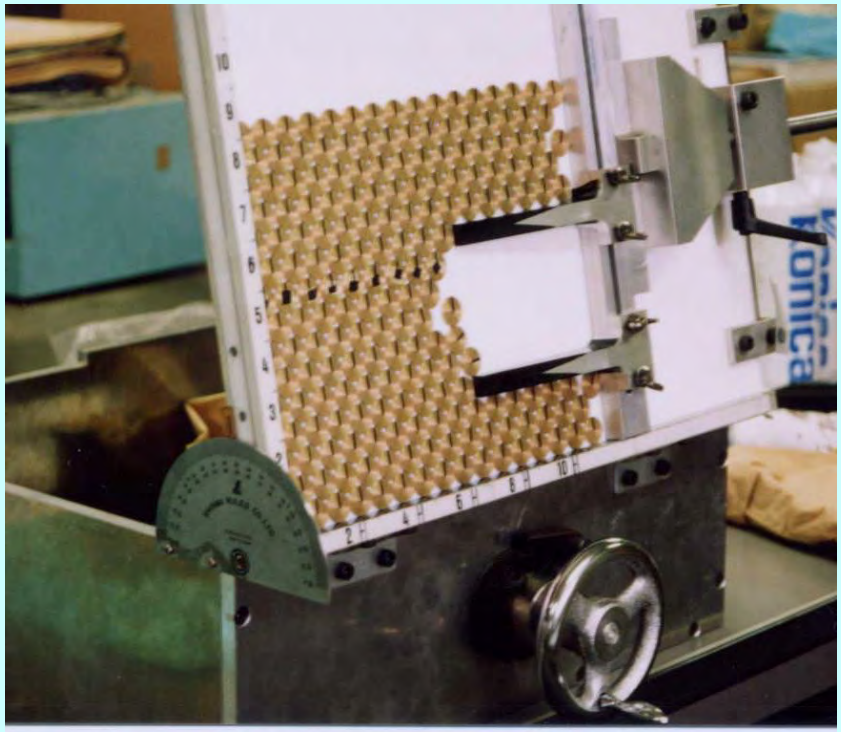


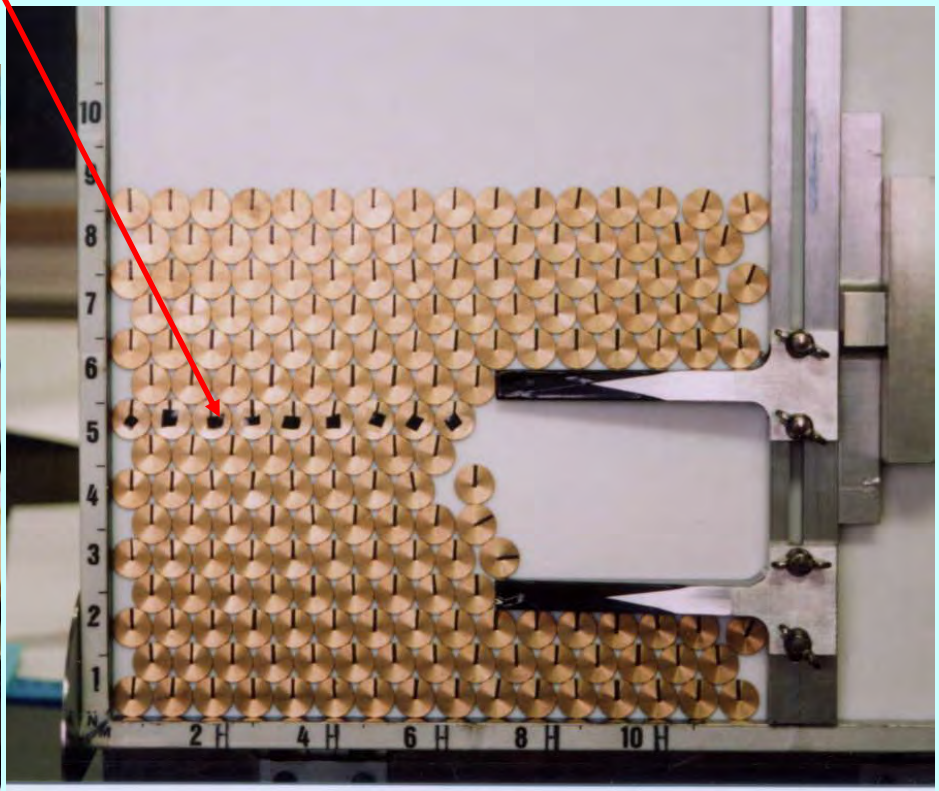




Make a clay layer

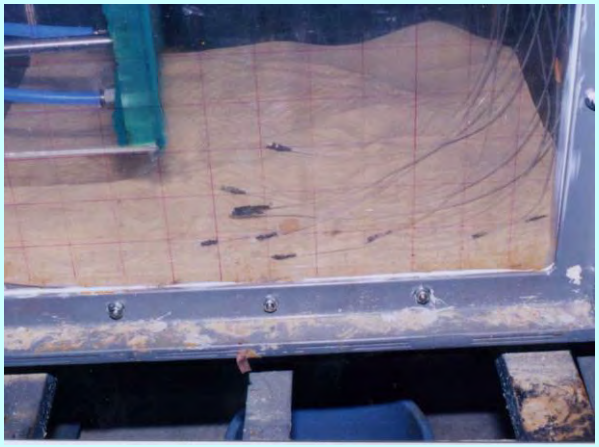
Clay layer

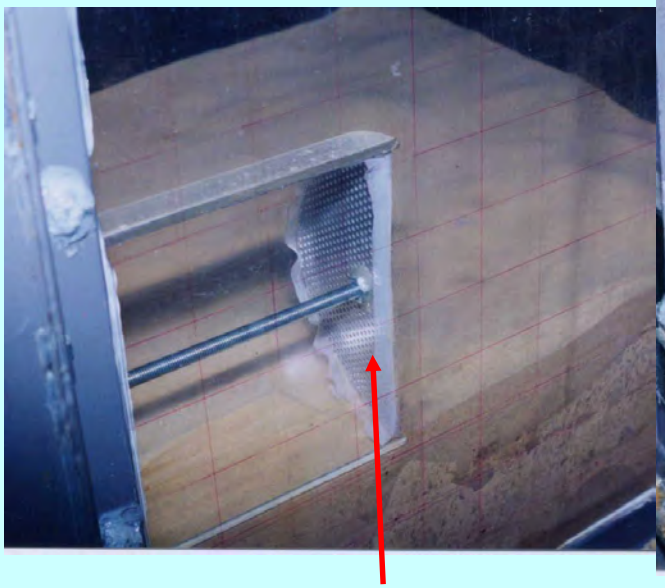




Simulate the test with a new numerical analysis method of granular material.

By water





Face board is made of punching metal

Pourer water from the bottom

release water from the vessel

Pourer water again

Excavation

Let’s bore tunnel actually!

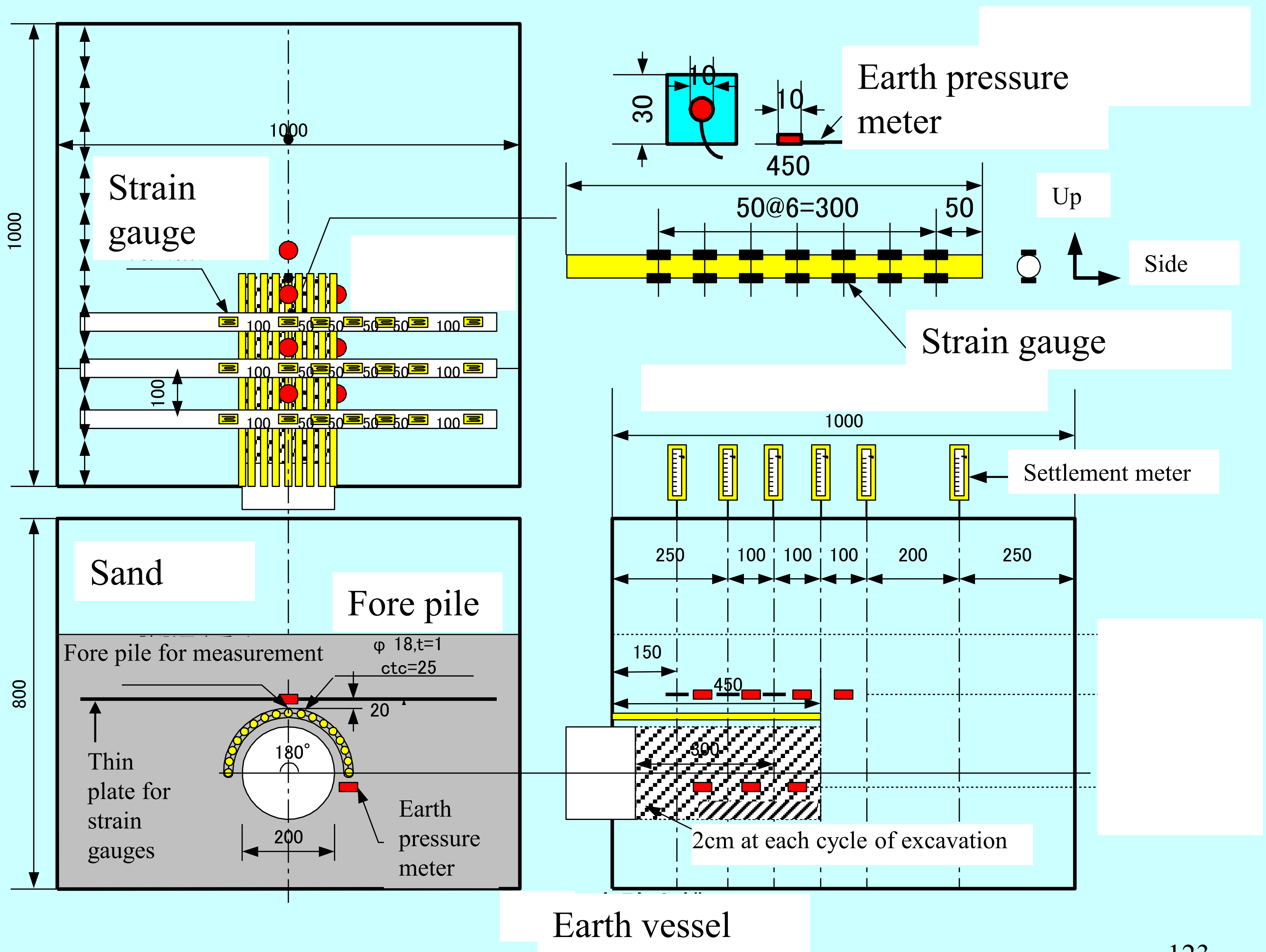
Set fore piles

Excavation

Head of the Tunnel

Measure a lot of points in the ground.

Another purpose, keeping our technique of experiment.



Earth pressure meter
30
10
10
450
50@6=300
50
Up
Side
Strain gauge
1000
Strain gauge
100
50
100
1000
Settlement meter
250
100
100
100
200
250
150
450
300
2cm at each cycle of excavation
800
Sand
Fore pile
Fore pile for measurement
φ 18,t=1
ctc=25
20
180°
200
Thin plate for strain gauges
Earth pressure meter
Earth vessel

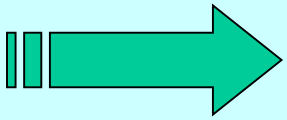
State of the tunnel and ground after removing fore piles.

(A face stand, although boring part is 40cm length)

(Thickness of sandy lining is 2cm)

When a little impact was given, the face collapsed.

Six methods (make a tunnel face collapse)

1. Pull a face board
2. Decrease a overburden
3. Increase height of a face
4. Increase gravity
5. **Water**  **Future subject**

   Most influential in face collapse!
6. Excavation

Thank you for your attention!