# Lessons on Behavior of Tunnel Ground

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Williamsburg

Edward J Cording
University of Illinois at Urbana-Champaign

# Lessons on Behavior of Tunnel Ground

1. Geology
2. Construction
3. Structures

Understanding the lessons in all three categories is critical for a successful tunnel project.

# Lessons on Behavior of Tunnel Ground

- 1. The geologic environment in which the tunnel is sited
- 2. The interaction of the ground with the construction process
- 3. The interaction of the ground with the tunnel structure

… *Over the past 70 years,*
*and even over the centuries,*
*Lessons in these areas have been learned and relearned,*
*and, in some cases, forgotten or ignored.*

1. The geologic environment in which the tunnel is sited

   - The lesson on the geologic environment and its relation to tunnel ground behavior should not be confined to the first chapter of a geotechnical report

   - It should be an integral part of the decision-making process throughout planning, design and construction of a tunnel project.

- Regional & local geology: what to expect, or to prove is absent
- Inspect continuous samples
  - Rock Core
  - Soil: sonic core
- Look at site and exposures
- Airphotos, old photos, old maps
  (Manhattan: Viele Topographic Map, Los Angeles fault scarps)

# 2. The interaction of the ground with the construction process

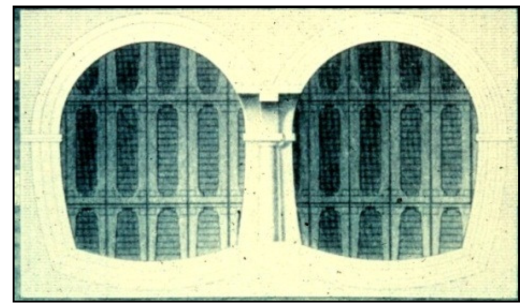
London, 1818: Patent application: Marc Isambard Brunel describes the objective of his tunnel shield to…

***"open… the ground in such a manner that no more earth shall be displaced than is to be filled by the shell or body of the tunnel."***

London: 1825 – 1841: Thames River

First subaqueous shield tunnel

40 feet wide, twin carriageways.

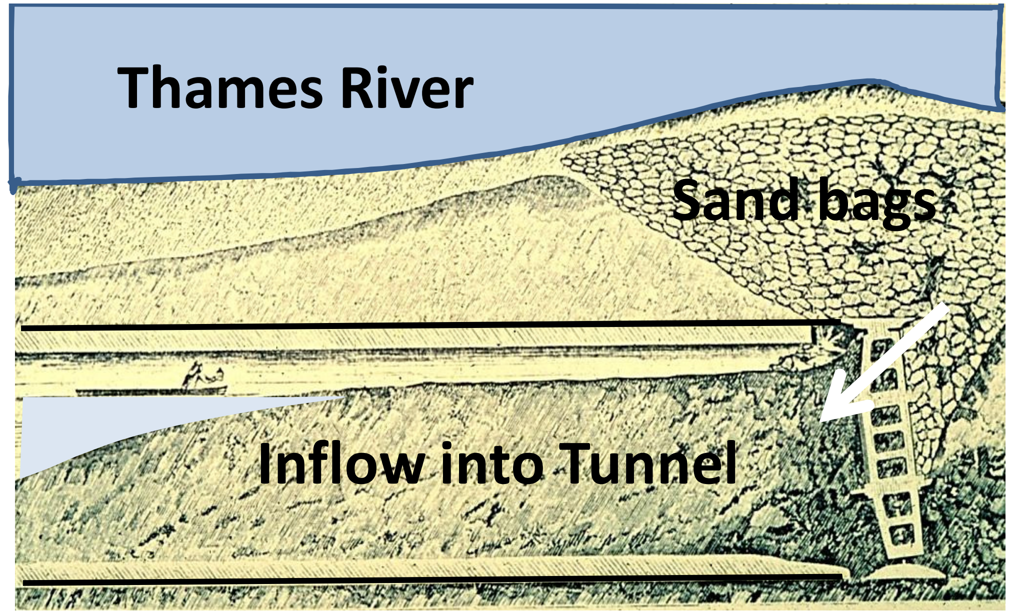


*Brunel made soundings & borings (found sand lenses under a blanket of clay), designed the tunnel, obtained financing, built the shield, directed construction, recovered from five floodings due to inflows of sand below a thinner than anticipated clay blanket, re-financed the project, rebuilt the shield under the river, finally broke into the shaft on the other side of the river…*

... *and, in 1841, was knighted by Queen Victoria*.

Figure 1-1

*Brunel’s tunnel remains in operation today on the London Underground*




- But Brunel was unable to…

***"open… the ground in such a manner that no more earth shall be displaced than is to be filled by the shell or body of the tunnel."***

As illustrated with the following cases, spanning the past 70 years, we have struggled to learn this lesson.

The lesson is finally being learned with current shield tunneling technology:

*An innovative monitoring program on a recent tunnel project explains why.*

# 2. The interaction of the ground with the construction process

- 2.1 1940: Chicago Subway: Liner plate tunnel (sequential excavation)
  *Link construction events to cause of large surface settlements*
  ***Blueprints of construction sequences, soil samples, surveys, squeeze tests***

- 2.2 1972: Washington DC Metro: open face digger shield
  *Obtain 3-dimensional pattern of ground movements around advancing shield*
  *Determine the source of large ground loss around the shield*
  ***Recording of plumb bob, laser line on plastic targets, soils exposed in tunnel face, extensometers, inclinometers***

- 2.3 2011: Sound Transit University Link, Capitol Hill Tunnel
  Pressurized face shields (Earth pressure balance)
  *Demonstrate how the Contractor's shield not only pressurizes and supports the tunnel face but pressurizes the annular gap (the overcut) around the shield and prevents settlement*
  ***Machine readouts, digital records, soils not visible, pressures around shield, piezometers, extensometers***

2.1  1938 – 1941

Chicago Subway,

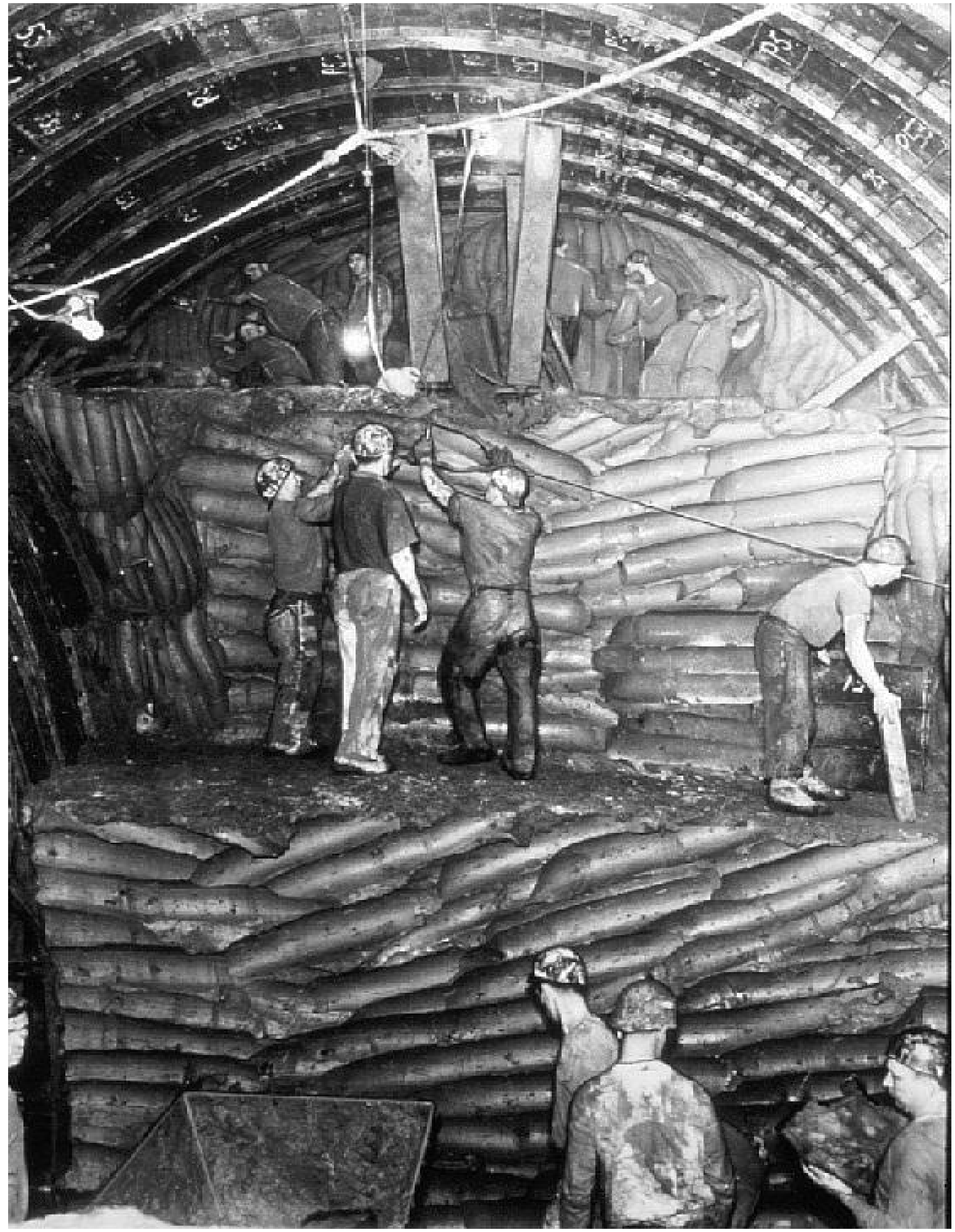
Karl Terzaghi &

Ralph Peck

Soft Chicago Clay

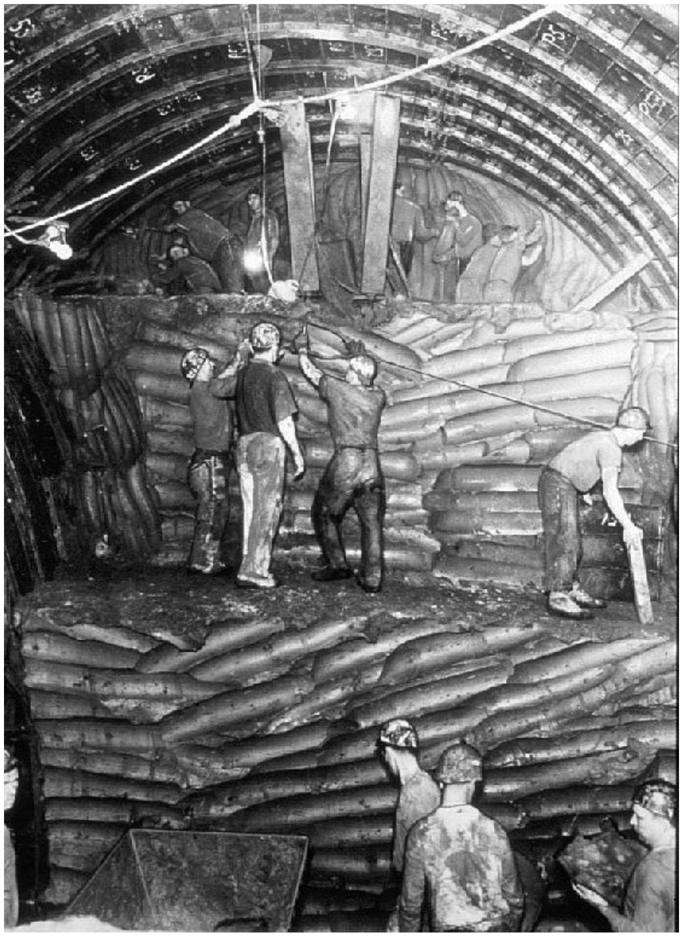
Primary objective:

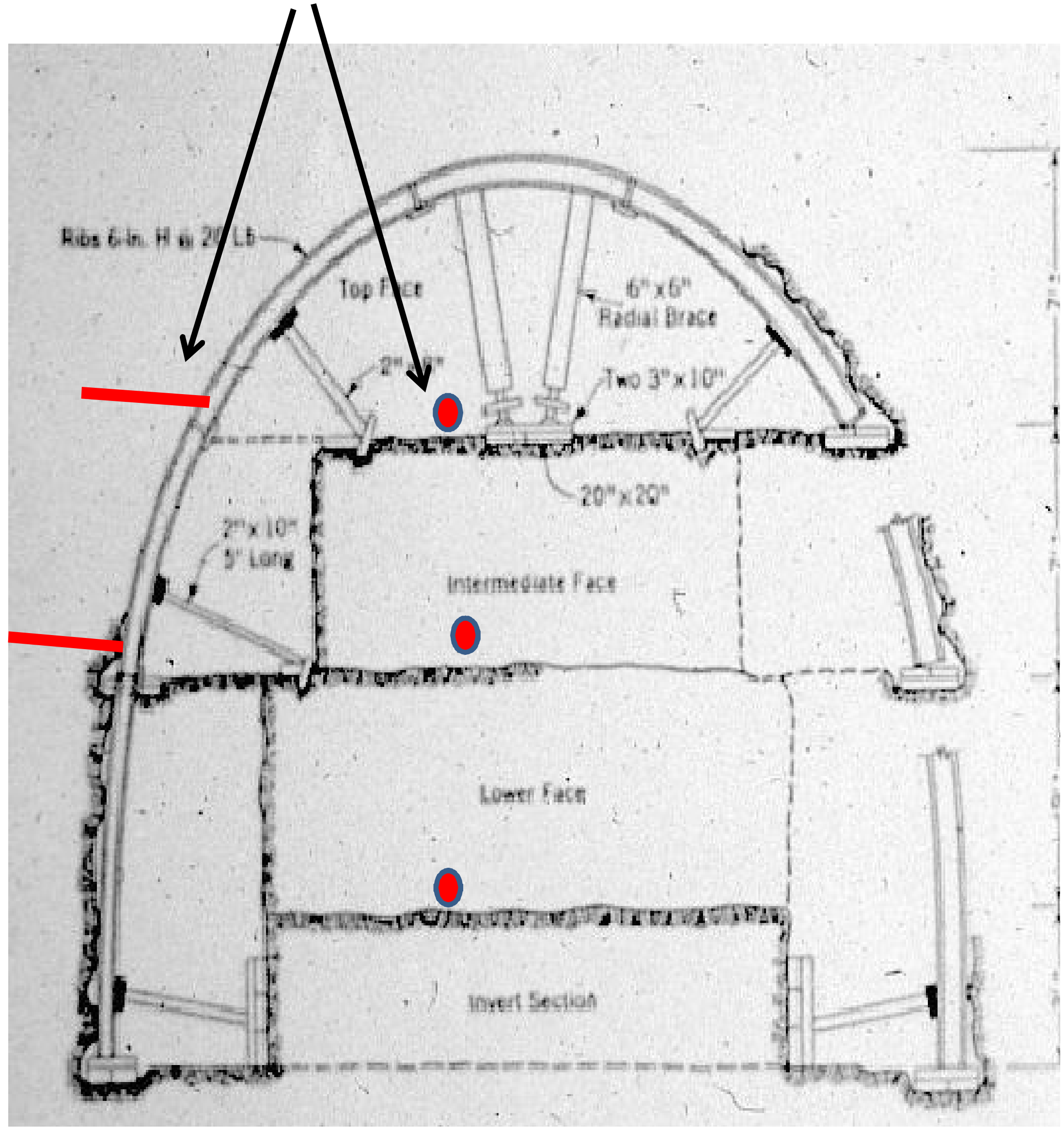
*Relate tunnel construction…*



*... to settlement at the surface*

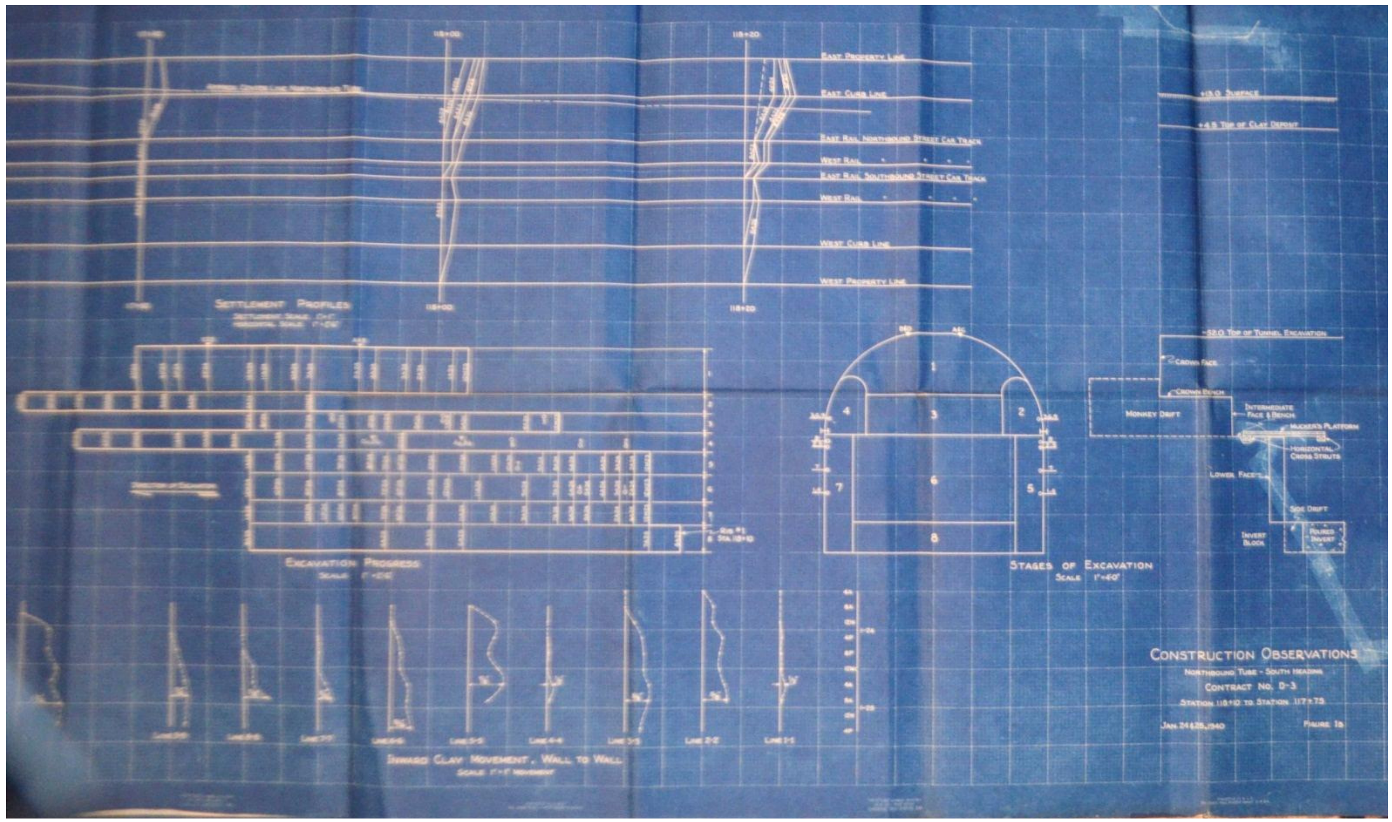
# Squeeze tests: Rods embedded into the clay






Survey ends of rods to measure ground movement into tunnel

- ….*Link Measurements with construction events:* *Squeeze test sections*
  - SURFACE SETTLEMENT PROFILES
  - EXCAVATION & SUPPORT SEQUENCE

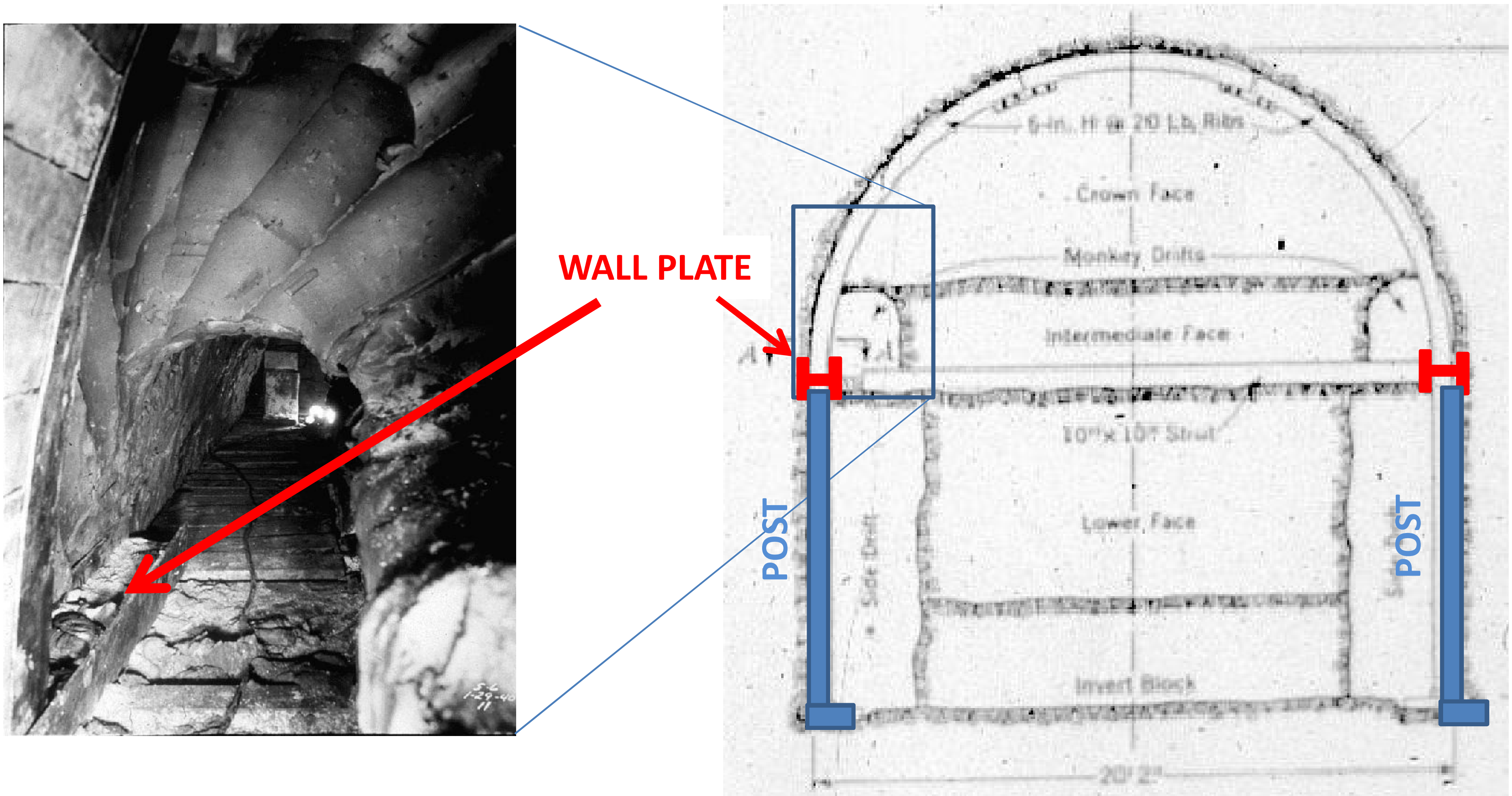



  - SQUEEZE TESTS (Displacement of clay into tunnel)

# Result: Excavation sequence was changed

Monkey drifts excavated **to allow placement of longitudinal wall plate**

**to support arch while posts were installed below**




Result : Surface Settlements reduced: 4 inches ⟶ 2 inches

# 2. The interaction of the ground with the construction process

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  *Link construction events to cause of large surface settlements*

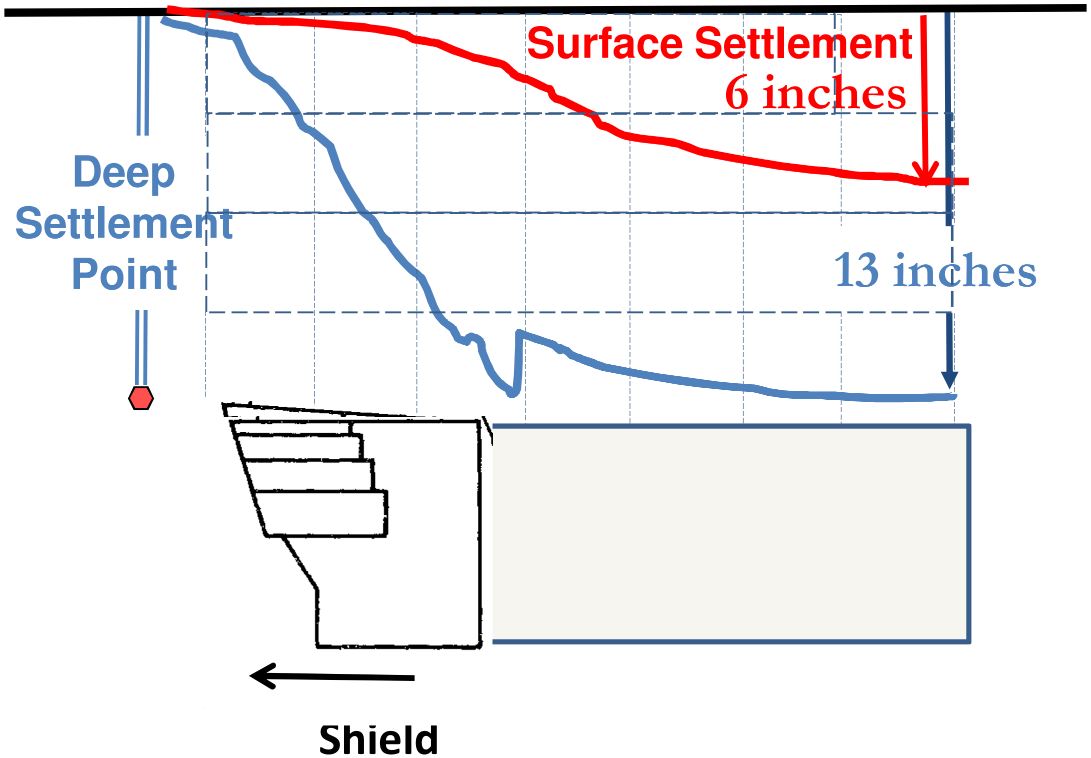
- 2.2 1972: Washington DC Metro: open face digger shield
  *Obtain 3-dimensional pattern of ground movements around advancing shield*
  *Determine the source of large ground loss around the shield*

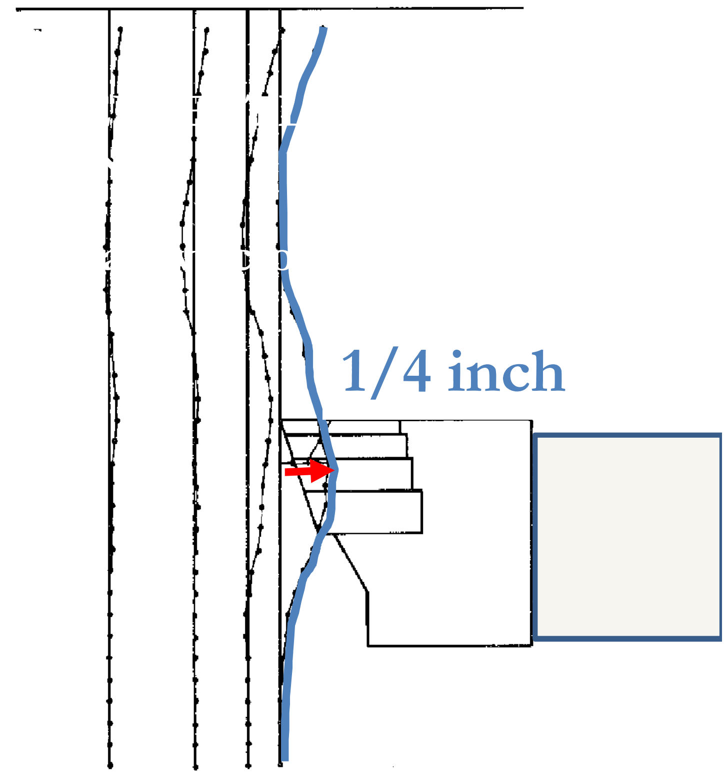
***Recording of plumb bob, laser line on plastic targets,***
***soils exposed in tunnel face,***
***extensometers, inclinometers***

# 2.2 1972: Washington Metro, Lafayette Square; Univ of Illinois

Alluvial sand, clay     Open-face digger shield

*Locate, evaluate source of ground loss*




**Deep settlement point – extensometer**

***Determine source of ground loss around shield***

**Monitor movements & tunnel construction events every shove of the shield**

**Inclinometer: measured lateral displacement into tunnel face**

***Confirm that face is not source of large ground loss***

Cording and Hansmire, 1974

# Result

- Shield hood rebuilt for second tunnel
- Surface settlements reduced from 6 to 2 inches

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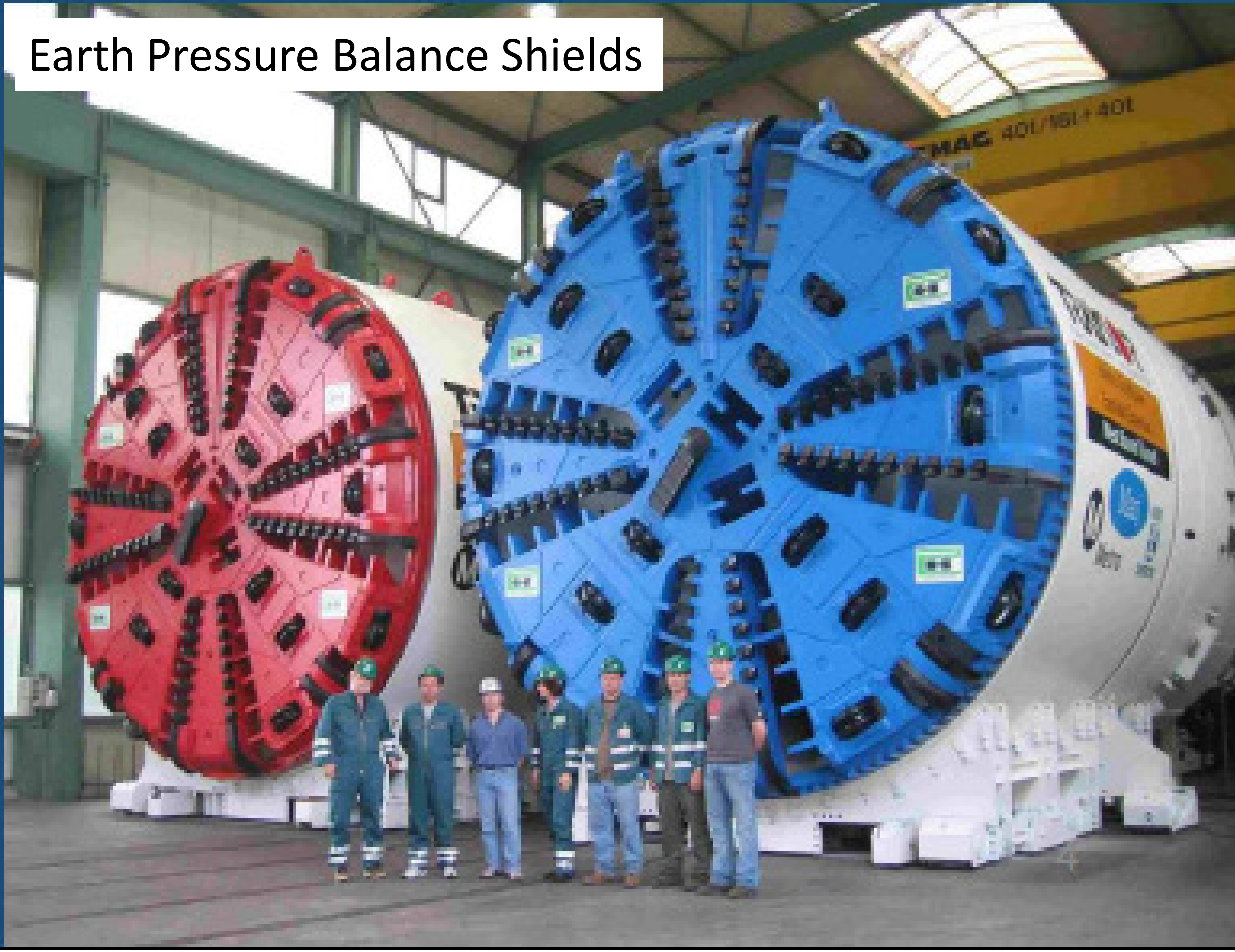
  *Demonstrate how the Contractor's shield not only pressurizes and supports the tunnel face but pressurizes the annular gap (the overcut) around the shield and prevents settlement*

***Machine readouts, digital records, soils not visible, pressures around shield, piezometers, extensometers,***

# Earth Pressure Balance Shields

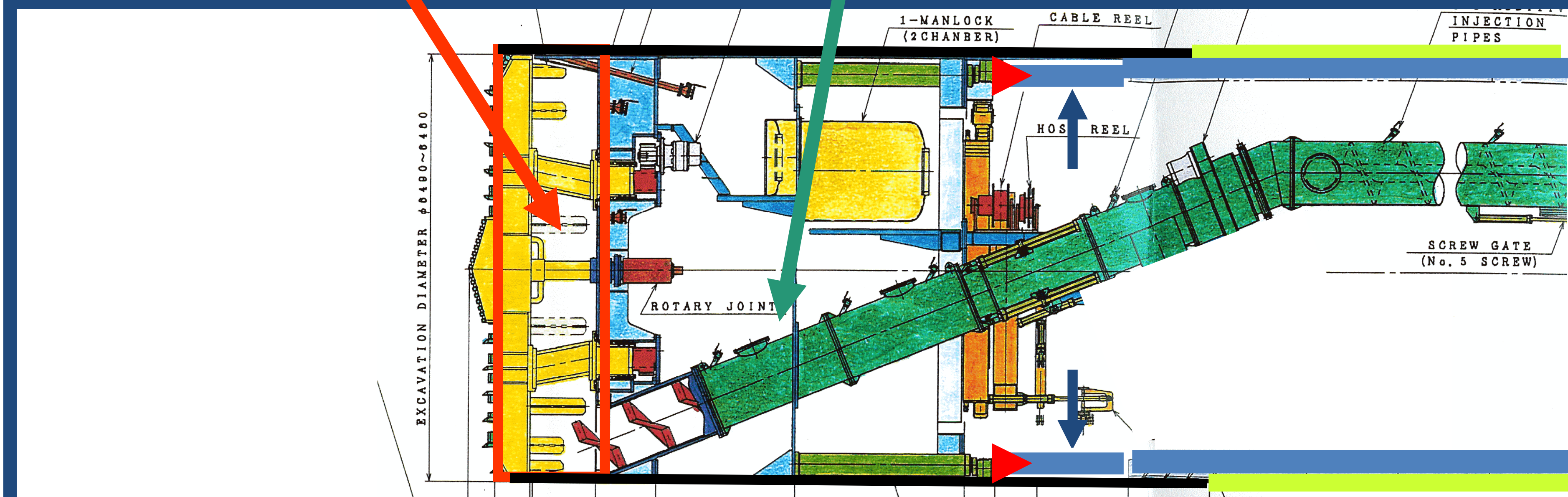


# Pressurized face:
# Earth Pressure Balance (EPB) Shield

**Pressurized and conditioned muck in chamber supports water and soil in face**

**Screw removes muck and provides back pressure**

**Lining erected in tail**



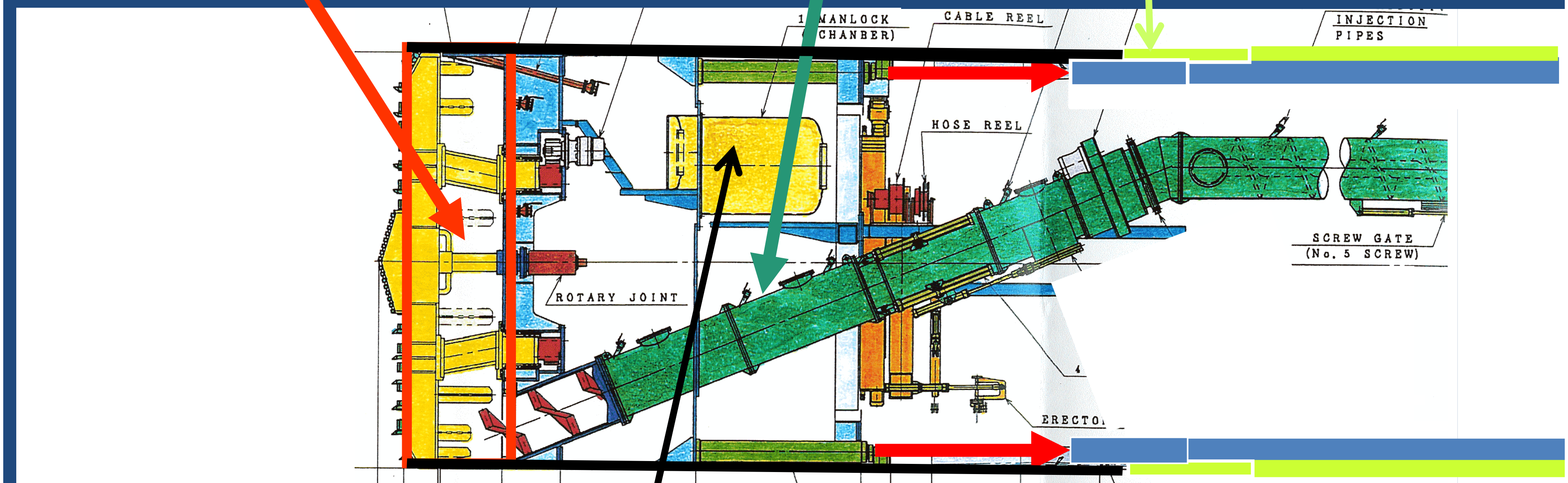
# Pressurized face:
# Earth Pressure Balance (EPB) Shield

**Pressurized and conditioned muck in chamber supports water and soil in face**

**Screw removes muck and provides back pressure**

**Lining erected in tail**

**Shield shoved & grout placed**




**Compressed air chamber for access to face (Intervention) to repair cutterhead and replace cutters.**

# Shield Tunneling: Control Sources of Ground Loss

Regular Ground loss

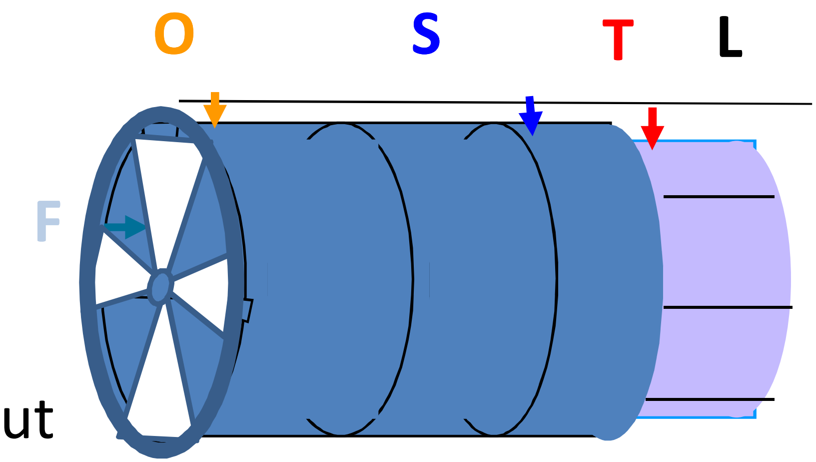
– **F**: FACE: Large, localized ground loss:
chimneys up due to run or flow of soil

– **O**: OVERCUT GAP

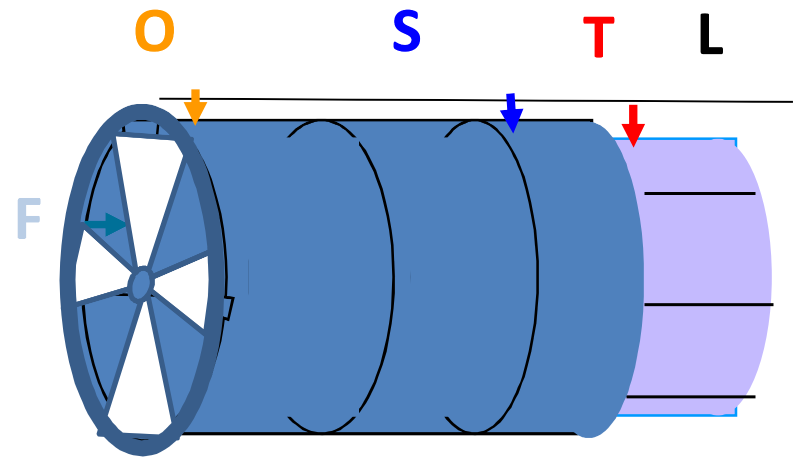
– **S**: SHIELD

– **T**: TAIL: fill with grout

– **L**: LINING

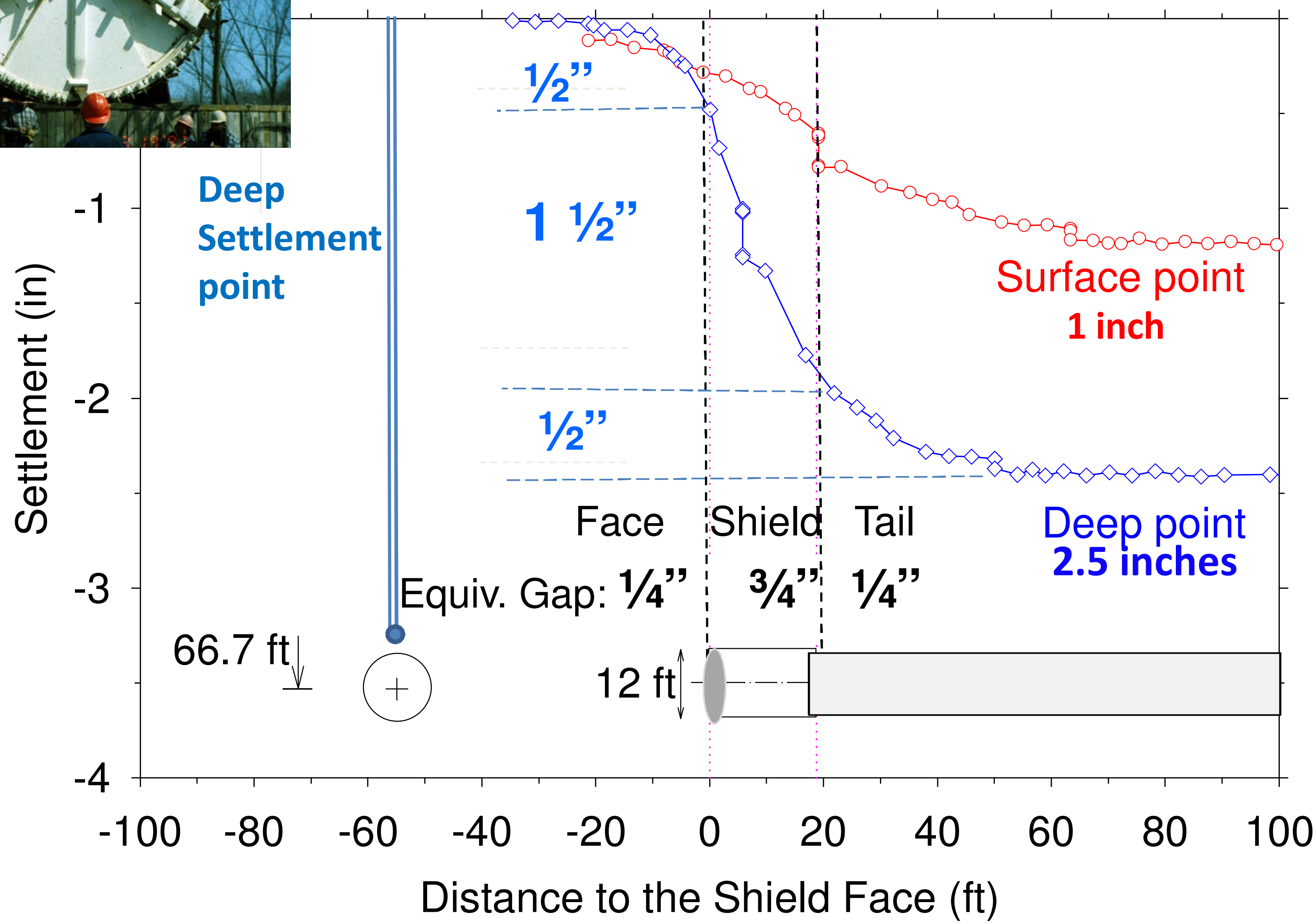


# Ground loss




- Open face shields:
  - Potential for soils to run or flow into face and cause large ground loss
  - Overcut gap aids steering and advance of shield but results in ground loss
    - A 3/ 4 -inch- thick gap will result in ~ 3/ 4 inches of surface settlement
- Closed face pressurized shields (EPB)
  - Pressure of excavated soil supports face
  - Is the overcut gap filled so that there will be no ground loss?

Open face shield (wheel excavator)
2000: Evanston, IL: Soft Chicago Clay
McNally Construction



# Closed face pressurized shields (EPB)

2011: Sound Transit JCM Ulink JV

University Link, Capitol Hill

Launch of
Earth Pressure
Balance Shield
From Capitol
Hill Shaft

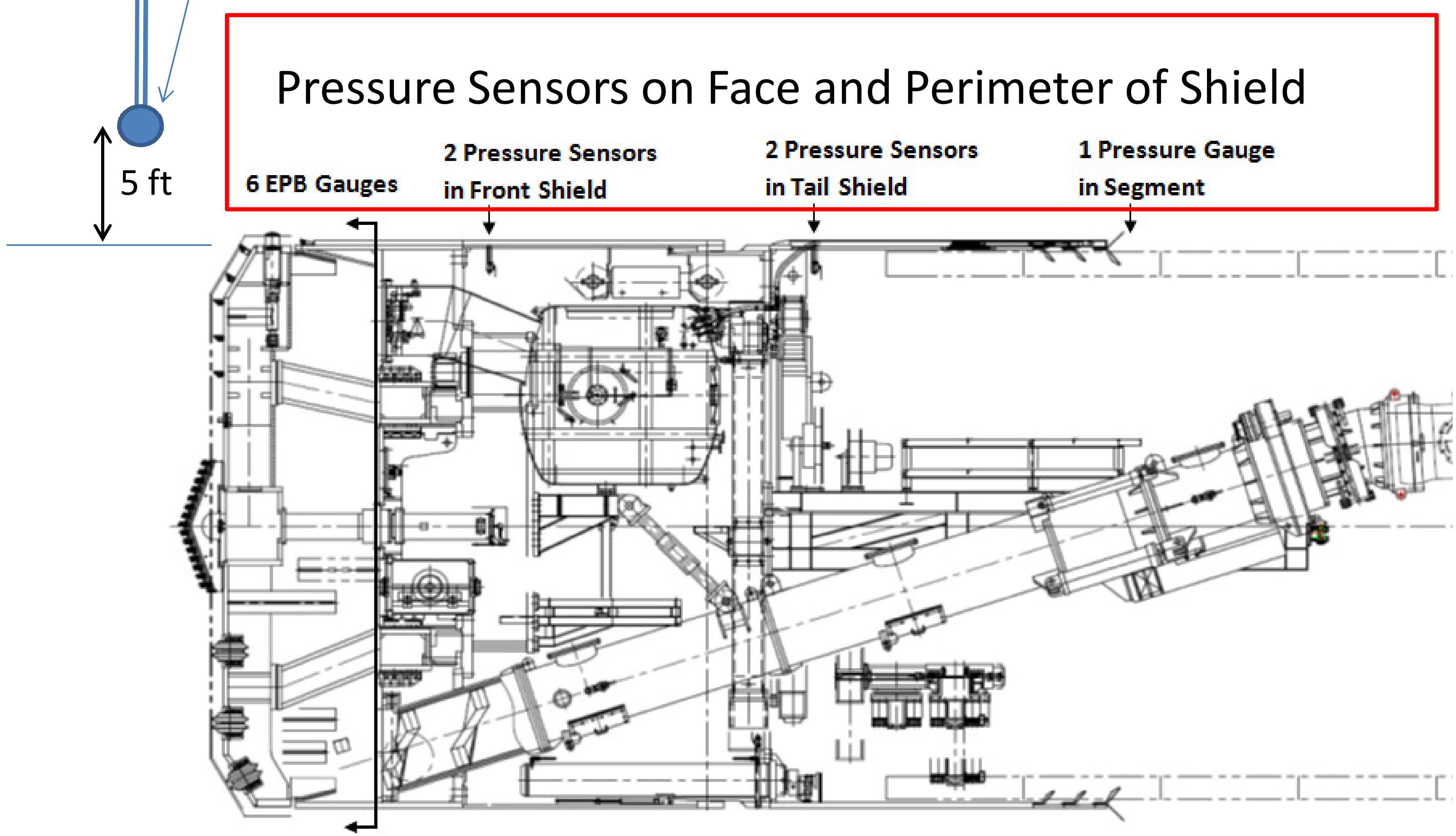
Glacial till,
outwash,
lacustrine clays

Capitol Hill

Cutterhead


REDUCE NUMBER OF INTERVENTIONS REQUIRED TO REPLACE CUTTERS AND REPAIR HARD FACING

Sound Transit JCM Ulink JV Test Sections:
Combined Deep Extensometer & Piezometer,
Continuously monitored




Diponio, et al, 2012, North American Tunnel Conference Proceedings, in press

# Sound Transit, Capitol Hill Trailing Gear for TBM

Sound Transit
Capitol Hill

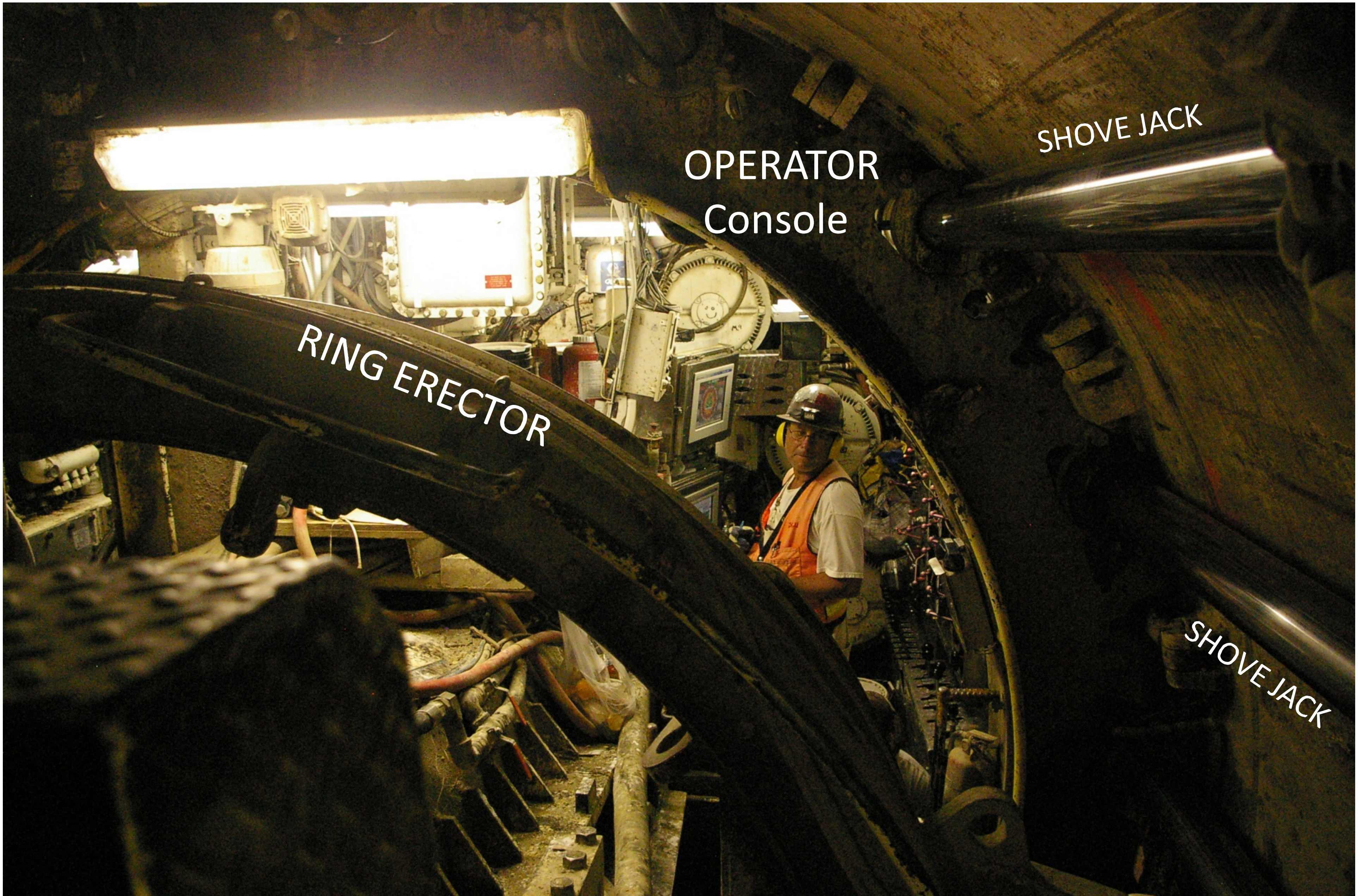
After TBM Launch


Reaction Frame
One concrete ring

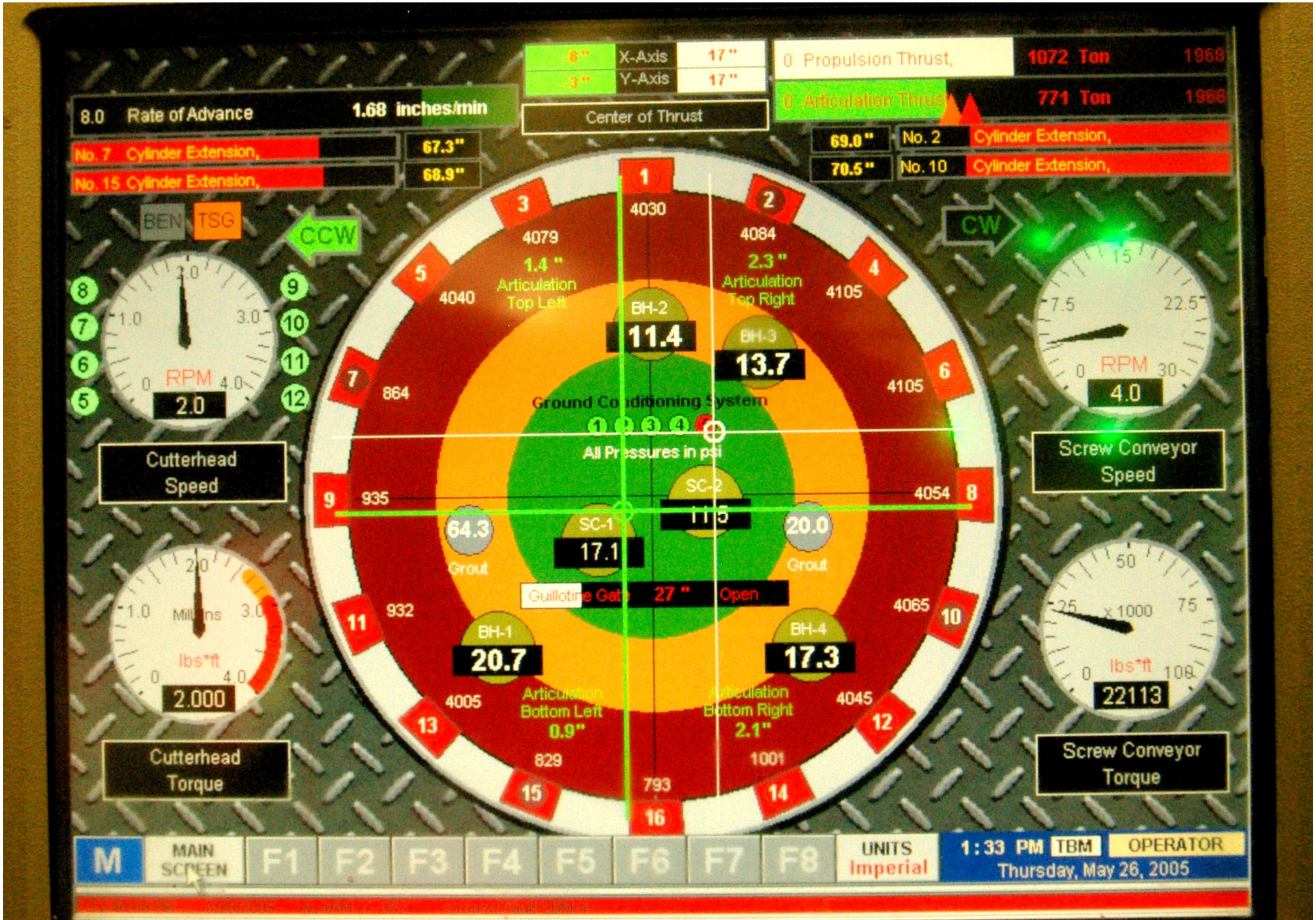

Concrete Segments, with gaskets
Erected in tunnel to form a 6-piece Ring


Segmental
Concrete Lining
in Tunnel

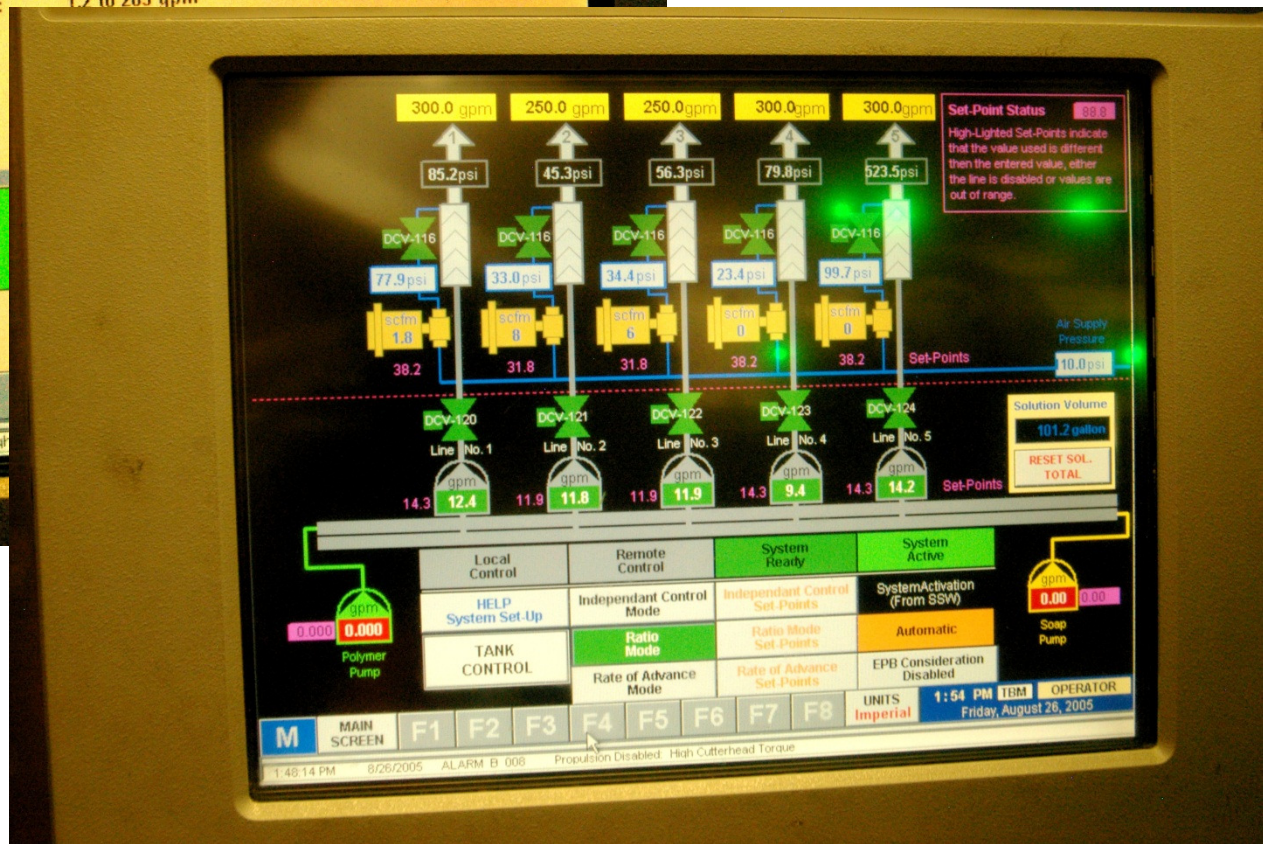

Walk forward to back of TBM


SHOVE JACK
OPERATOR
Console
RING ERECTOR
SHOVE JACK


Allen-Bradley
Allen-Bradley
UNION
Destin




Cutterhead Pressure in face and screw Screw Conveyor


# Conditioning of muck in chamber

**Separate lines for injecting (soap) foam, polymer, bentonite**


ALIGNMENT OF SHIELD TV: VISCOUS MUCK AT BACK OF SCREW

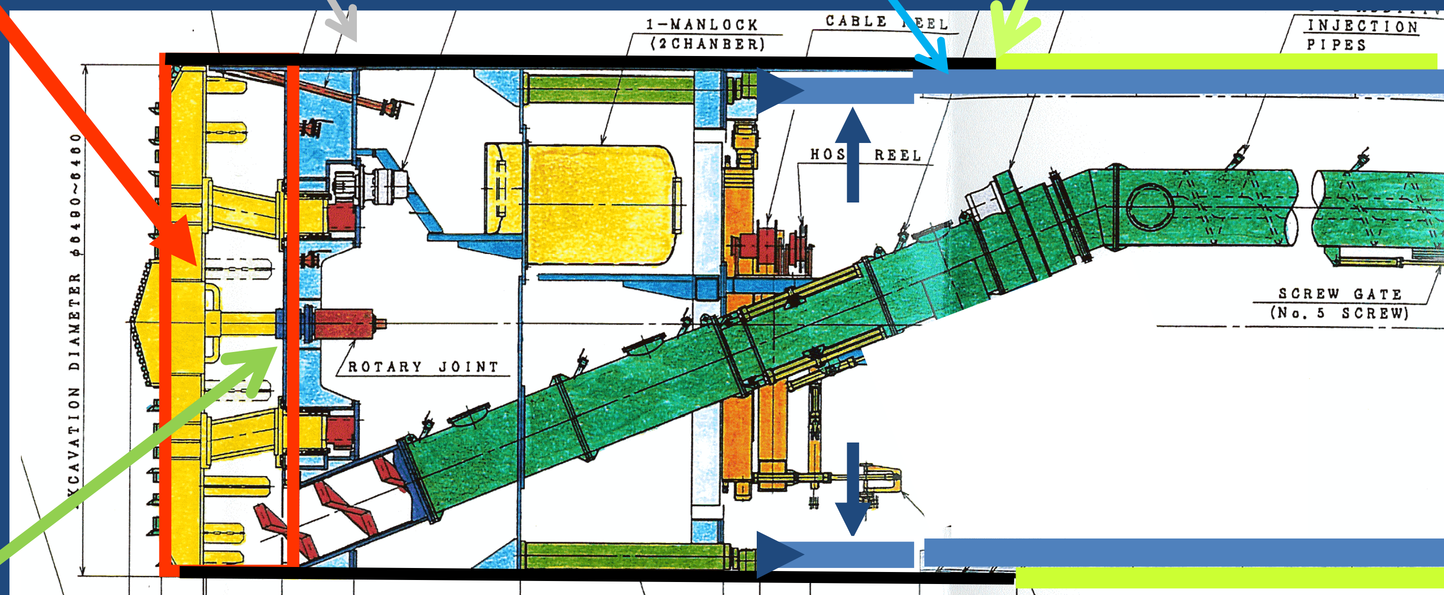
# Control of fluids with Earth Pressure Balance (EPB) Shield

Foam, polymer conditioners into face: separate valves and feed lines

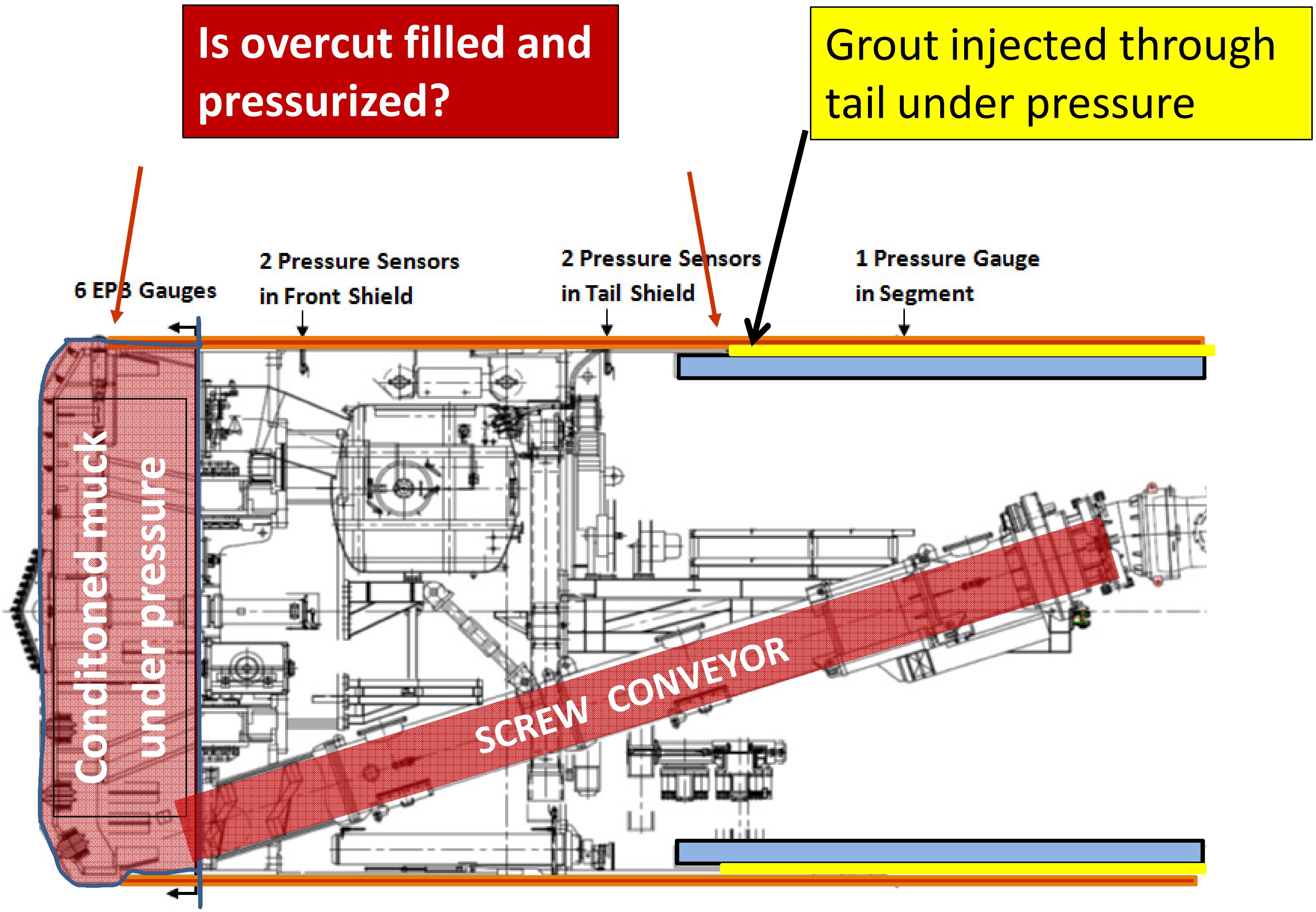
Bentonite injection around shield

3 rows of Tail brushes: grease injection: 4 + ports

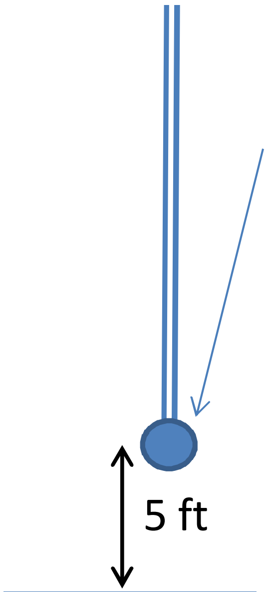
Lines through shield tail for injection of grout: Control pressure, volume



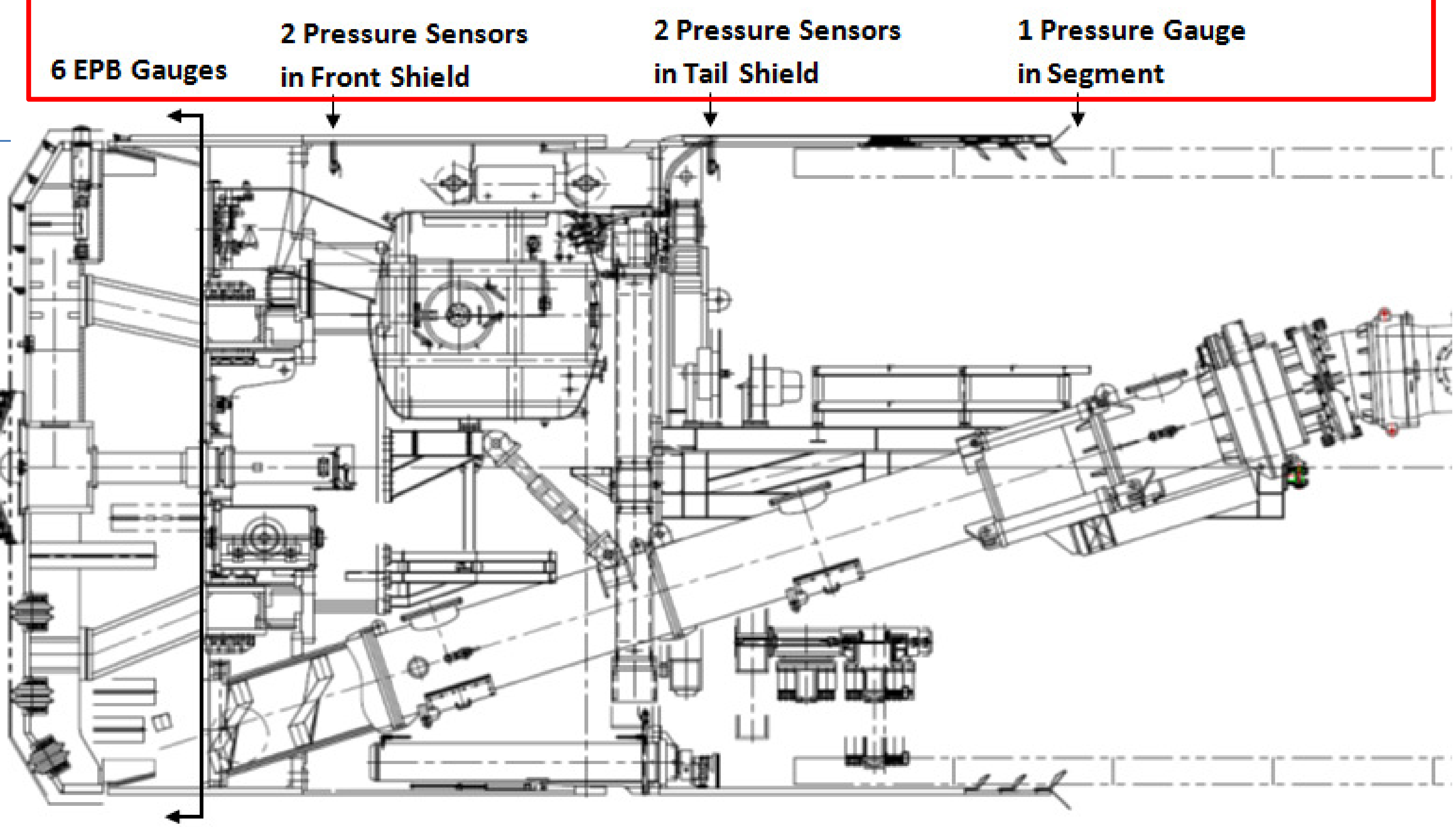

Pressure gages in chamber & screw: Control face pressure with screw


Is overcut filled and pressurized?
Grout injected through tail under pressure
6 EPB Gauges
2 Pressure Sensors in Front Shield
2 Pressure Sensors in Tail Shield
1 Pressure Gauge in Segment
Conditoned muck under pressure
SCREW CONVEYOR

Sound Transit JCM Ulink JV Test Sections:
Combined Deep Extensometer & Piezometer,
Continuously monitored




Pressure Sensors on Face and Perimeter of Shield




Diponio, et al, 2012, North American Tunnel Conference Proceedings, in press

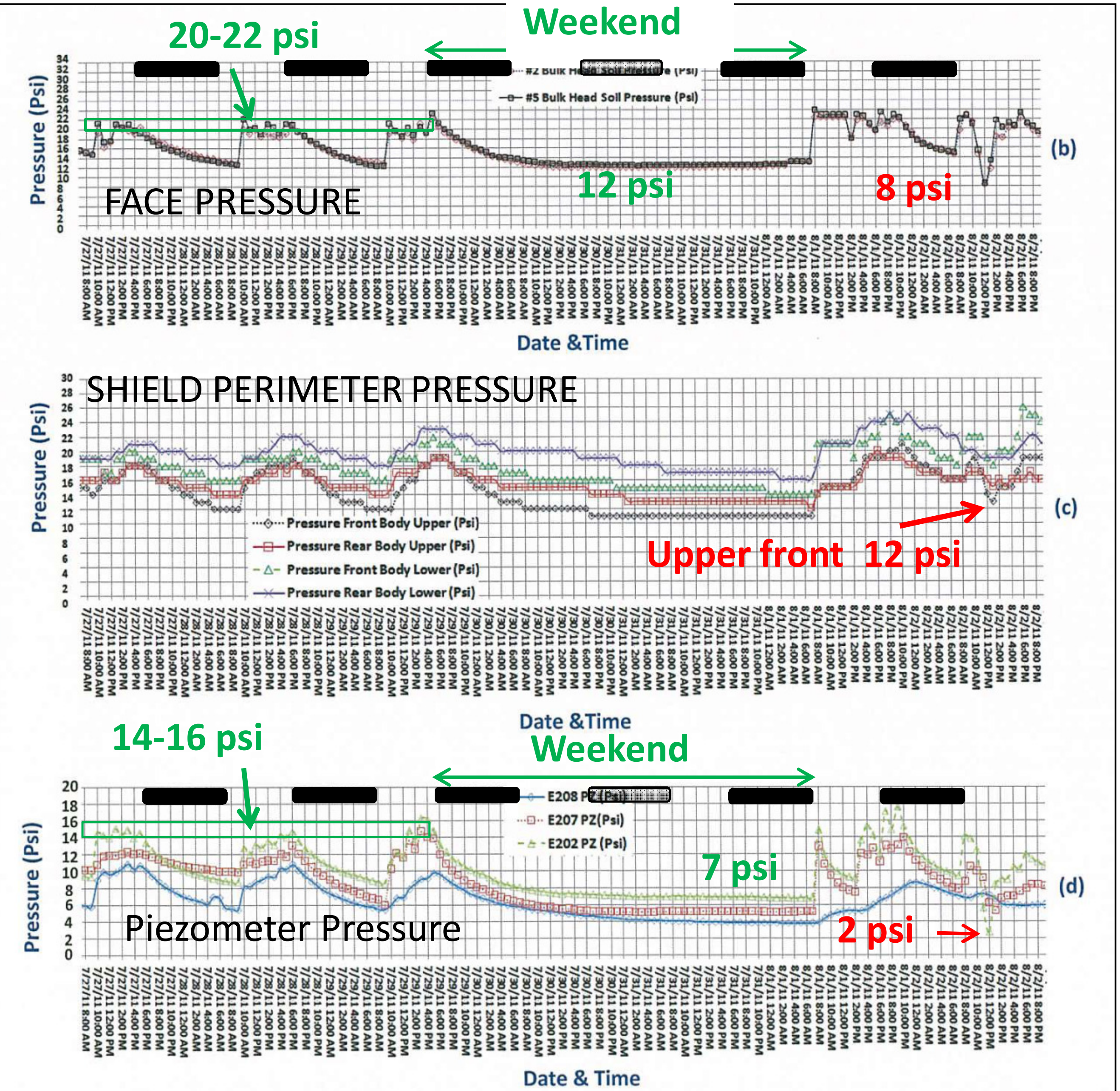
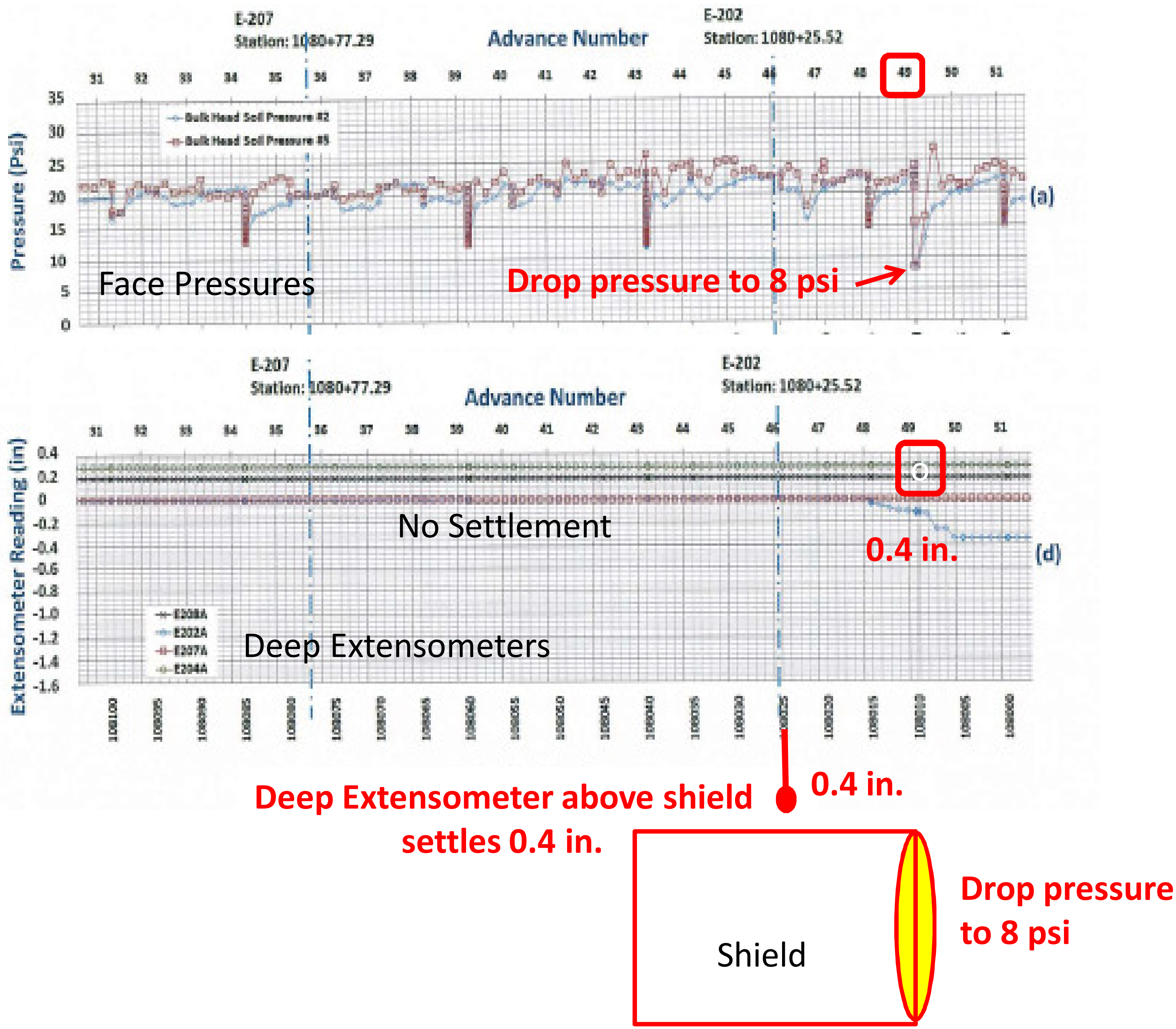
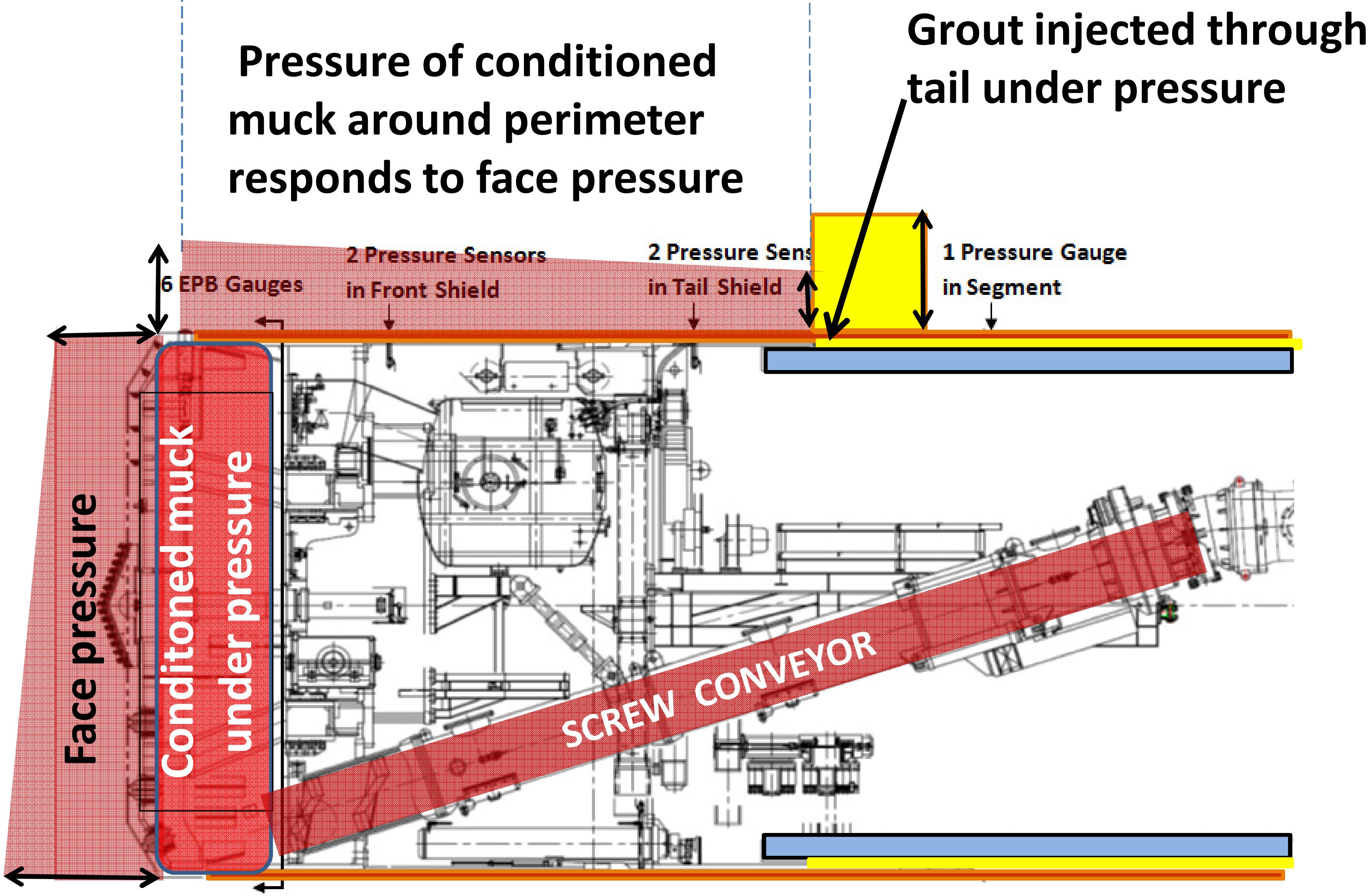



*Fig.10. (a) Advance number (b) Face Pressures (c) Body Pressures (d) Piezometer Pressures versus time*


E-207
Station: 1080+77.29
Advance Number
E-202
Station: 1080+25.52
Pressure (Psi)
Bulk Head Soil Pressure #2
Bulk Head Soil Pressure #5
(a)
Face Pressures
Drop pressure to 8 psi
E-207
Station: 1080+77.29
Advance Number
E-202
Station: 1080+25.52
Extensometer Reading (in)
No Settlement
0.4 in.
(d)
E208A
E202A
E207A
E204A
Deep Extensometers
Deep Extensometer above shield settles 0.4 in.
0.4 in.
Shield
Drop pressure to 8 psi

0

# Pressure Diagram



# Control of the ground

- Open shields
  - *Operator cannot be successful in all ground conditions*
- Pressurized face machines (EPB):
  - *Operator can control the ground*
- By understanding, setting target and warning levels, monitoring, and controlling key operational parameters in real time
  - *Operator, contractor & construction manager team can ensure that ground is controlled*

Achieving Marc Isambard Brunel’s objective:

***to “open… the ground in such a manner that no more earth shall be displaced than is to be filled by the shell or body of the tunnel.”***

## 2.3 The interaction of the ground with the construction process: pressurized face shields

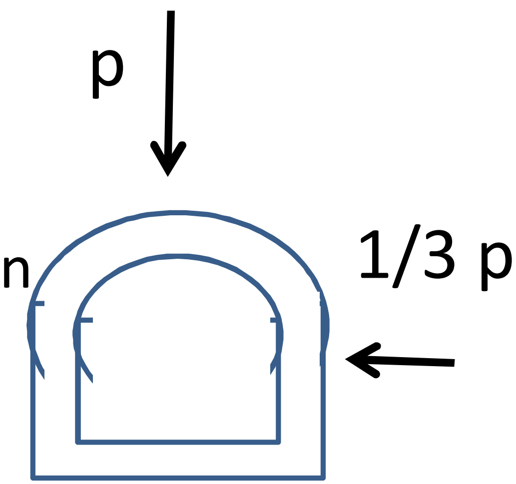
Geotechnical interaction with

Construction
Instrumentation
Mechanical – machine design
Chemical - conditioners
Gas
Compressed air interventions

# 3. The interaction of the ground with the tunnel structure

## 3.1 1940: Chicago Subway

- Terzaghi Recommends thin, flexible tunnel linings
    - With small deflections will develop uniform soil reactions and low bending moments




- He was not successful in changing City design
    - Assume large differentials between vertical and lateral soil pressures
    - High calculated bending moments
    - Thick concrete linings.

# 3. The interaction of the ground with the tunnel structure

## 3. 2 1972: New York Second Avenue Subway

Elastic beam/spring models become available,
permit evaluation of ground/structure interaction

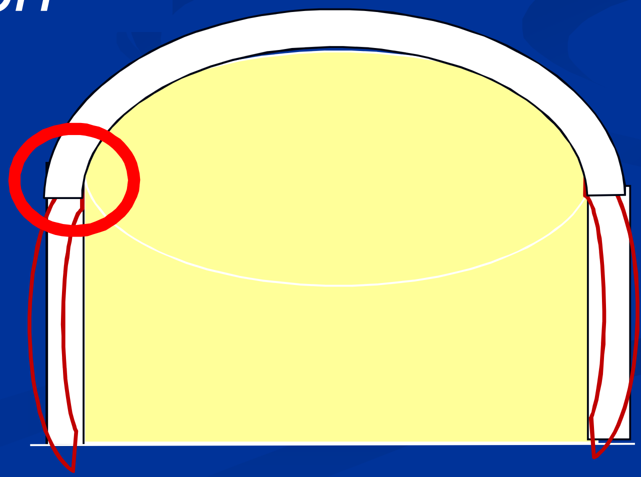
# Earlier NYCTA practice

*Non-reinforced concrete linings*

*Analyze arch and wall as separate arches*

*Allowable tension criterion*

*Ignore stresses at haunch*



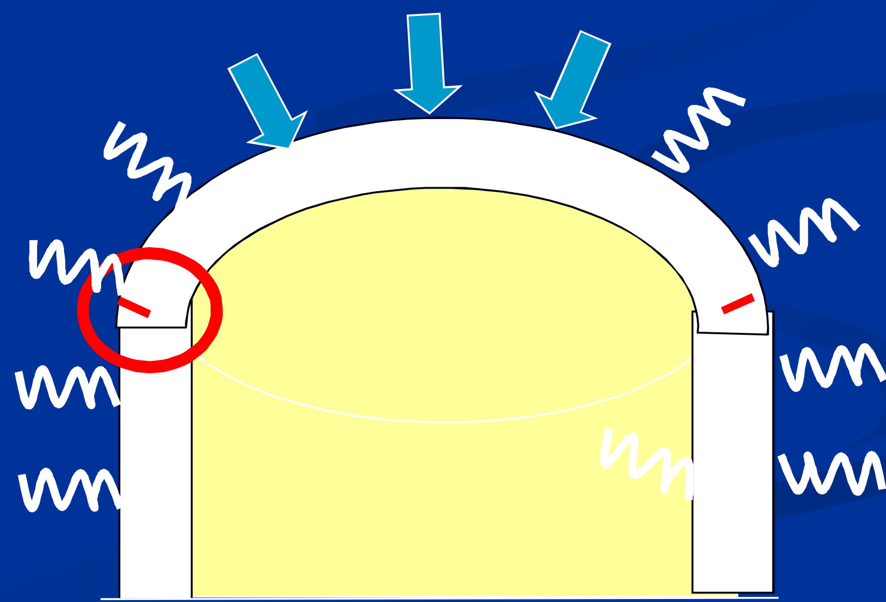
# 1972: NYCTA Second Ave Subway

*New elastic Beam- Spring analyses produce high elastic moments at haunch*

*& local tensile stresses exceed NYCTA allowable*

*Thickening lining does not reduce moments significantly*

***Analysis produces very thick linings, inconsistent with previous practice***

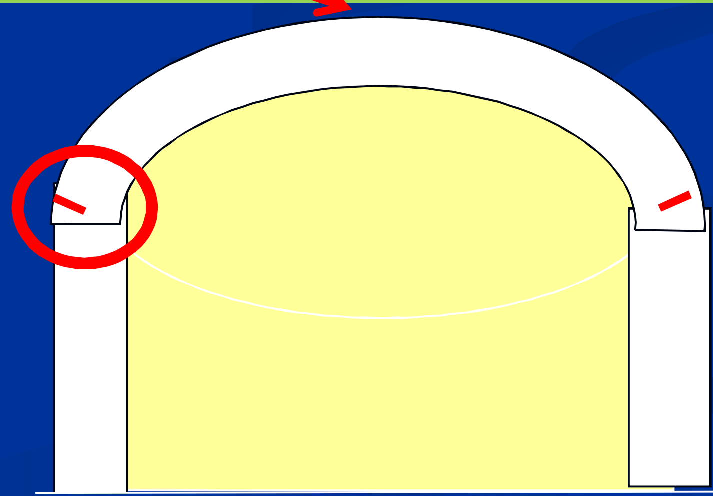


# 1972: NYCTA Second Ave Subway

*New elastic Beam- Spring analyses produce high elastic moments at haunch.*

***Very thick linings reduce clearances to existing subways.***

Existing subway



- 1972: NYCTA
  - In order to obtain reasonable lining thickness:
    - higher tensile stresses were allowed at the haunch, at least on exterior face.

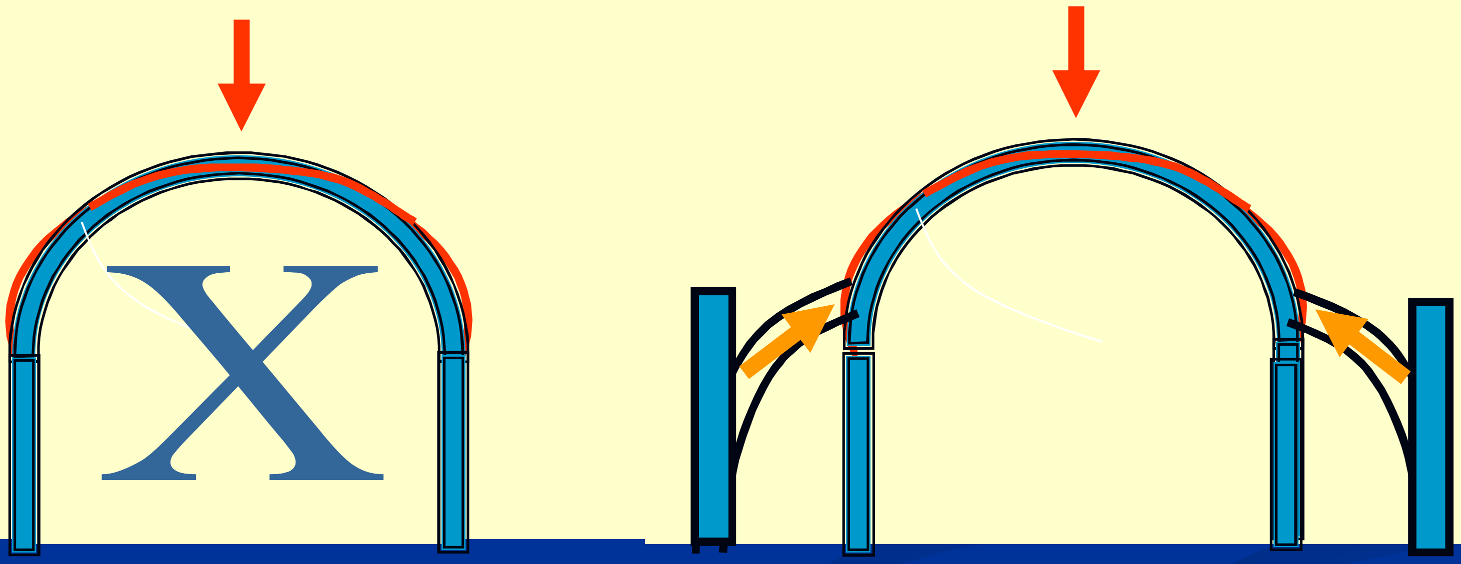
- 1972: Washington Metro
  - Calculated tensile stresses were handled by adding reinforcement to satisfy the analysis.

# 3.3 Lessons on tunnel lining stability began many centuries ago

- Buttresses
- Arches
- Ultimate Capacity of
  Concrete Tunnel Linings

**Roman arches**
**12th century cathedrals**
**Brick arch sewers**

# BUTTRESSES

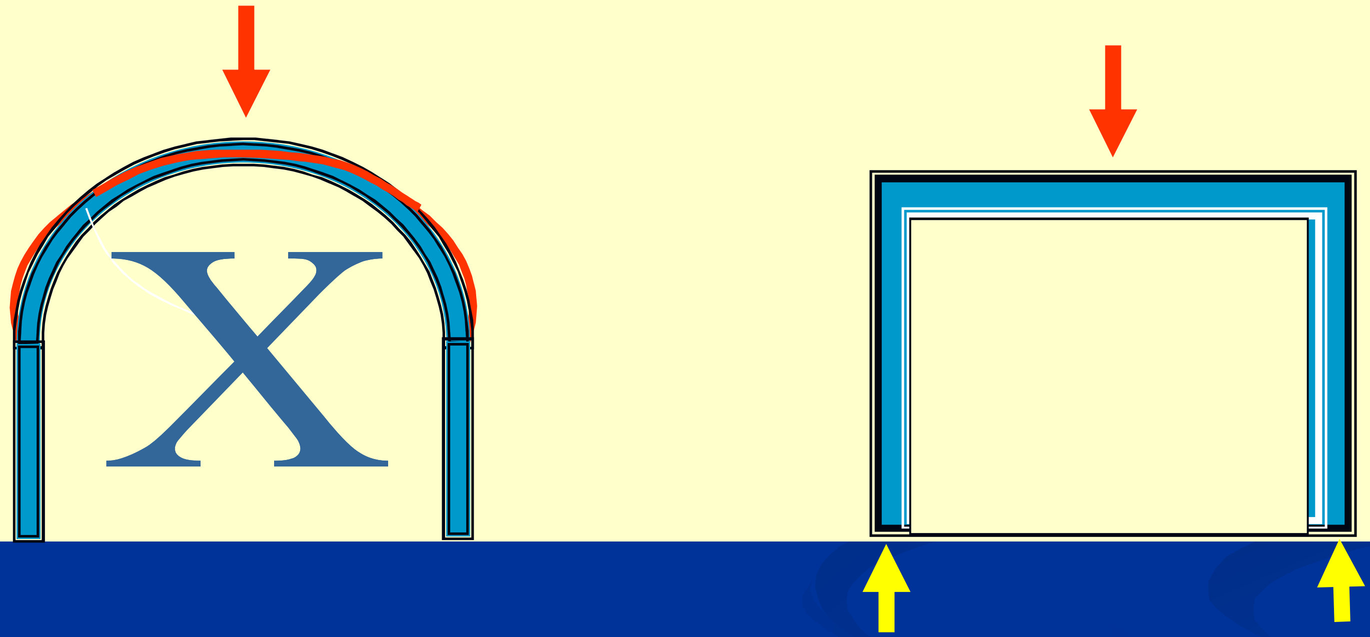



Above ground:

Cathedrals built with stone

Buttress keeps thrust within section

# "THE ADVANTAGE OF BEING A BEAM"

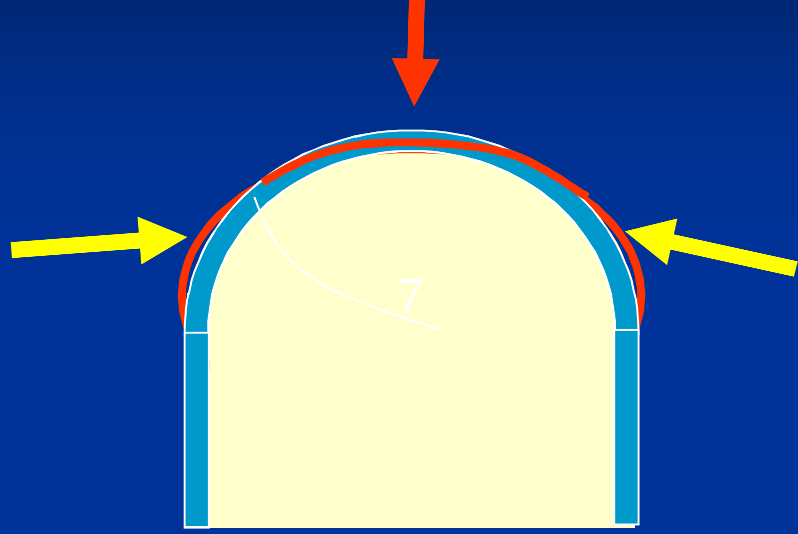



No buttress needed

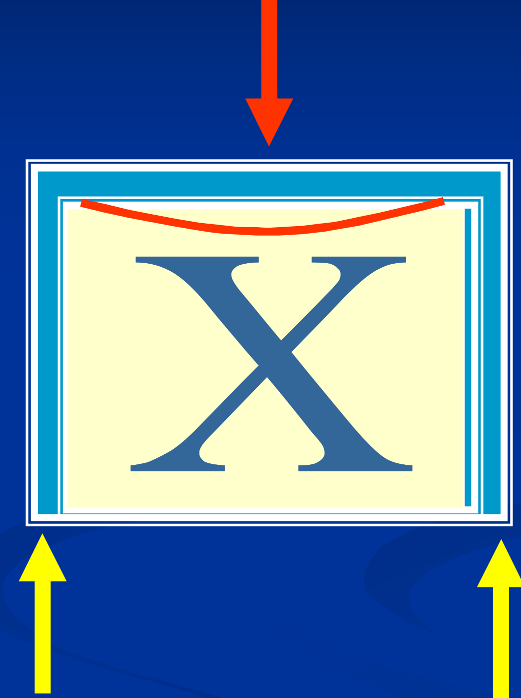
High rises can be built

# "THE ADVANTAGE OF BEING A BEAM"

# UNDERGROUND ?



B



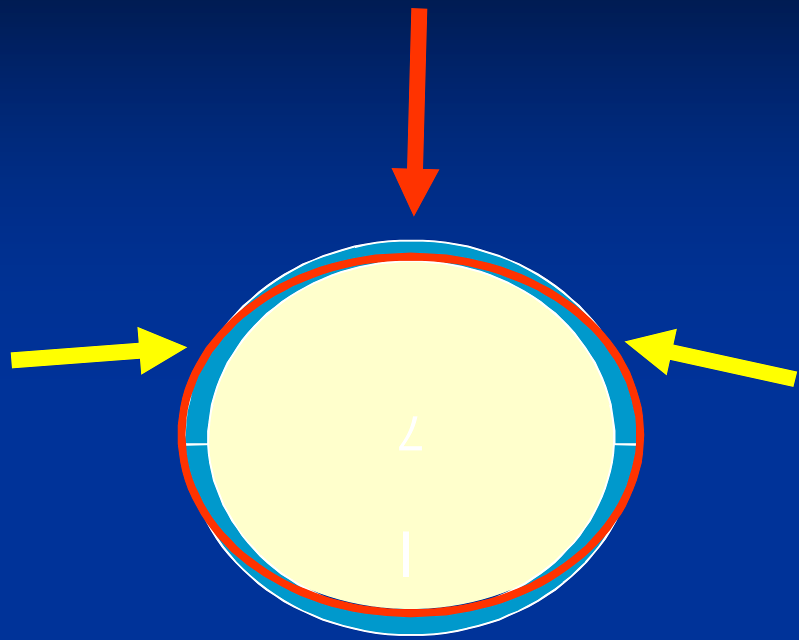
Unlimited rock buttress

Arch:  Low moments

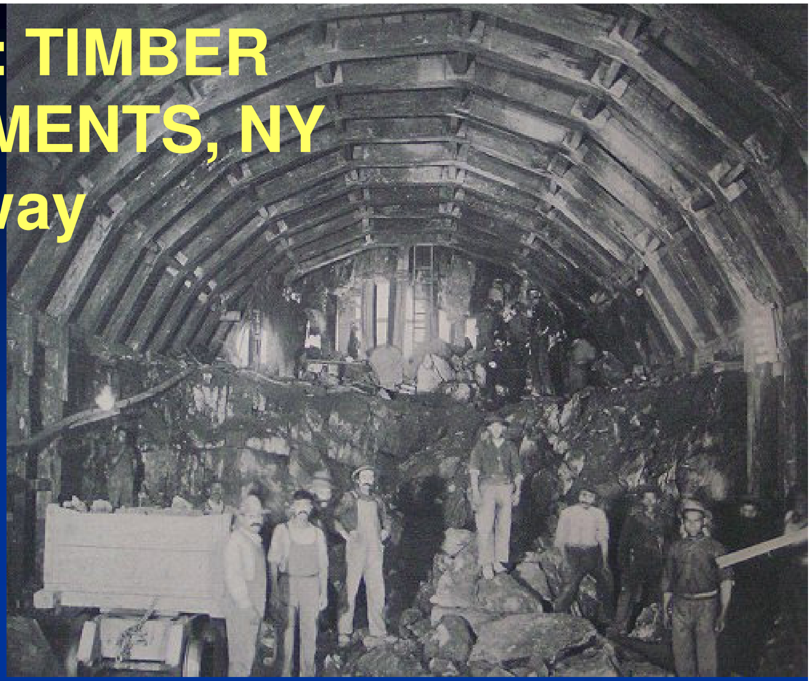
High rock loads

Beam:  High moments

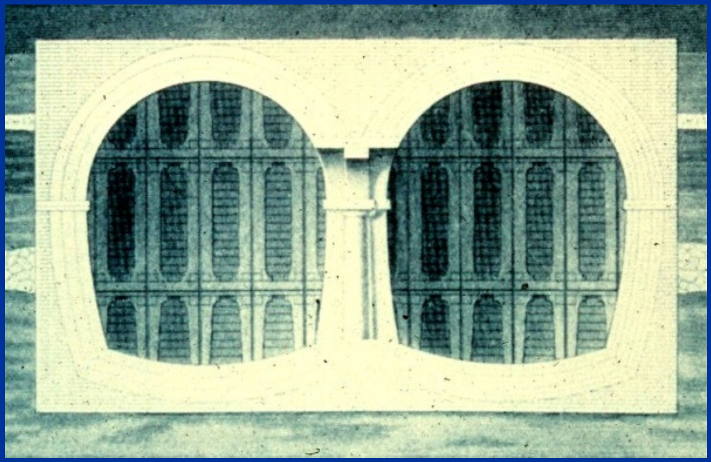
# BUILD ARCHES UNDERGROUND



1906: TIMBER SEGMENTS, NY Subway



2002: SPRAYED SHOTCRETE & light steel lattice girders

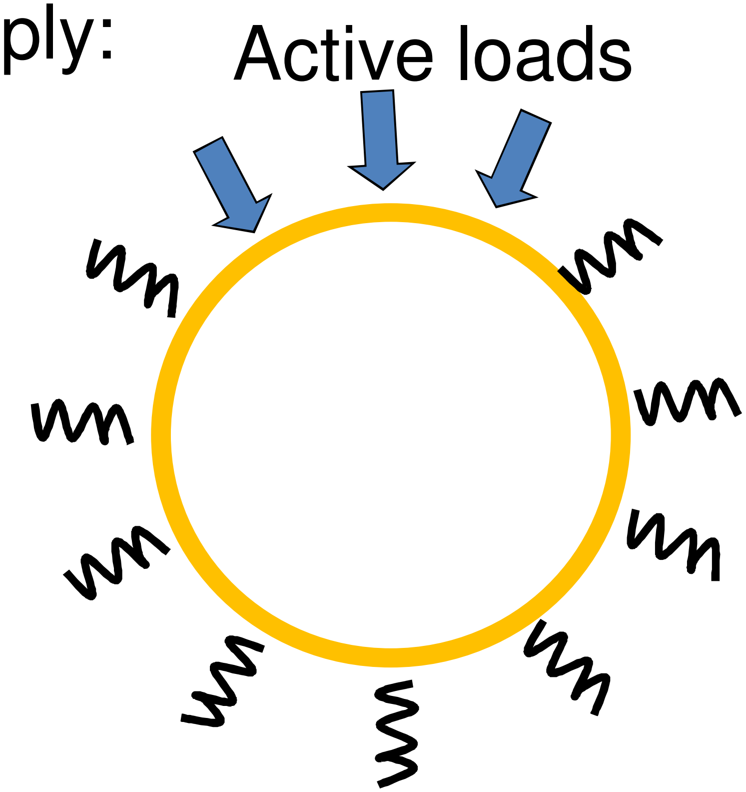


1841: Brick: Thames Tunnel

# …IN CONTACT WITH THE GROUND

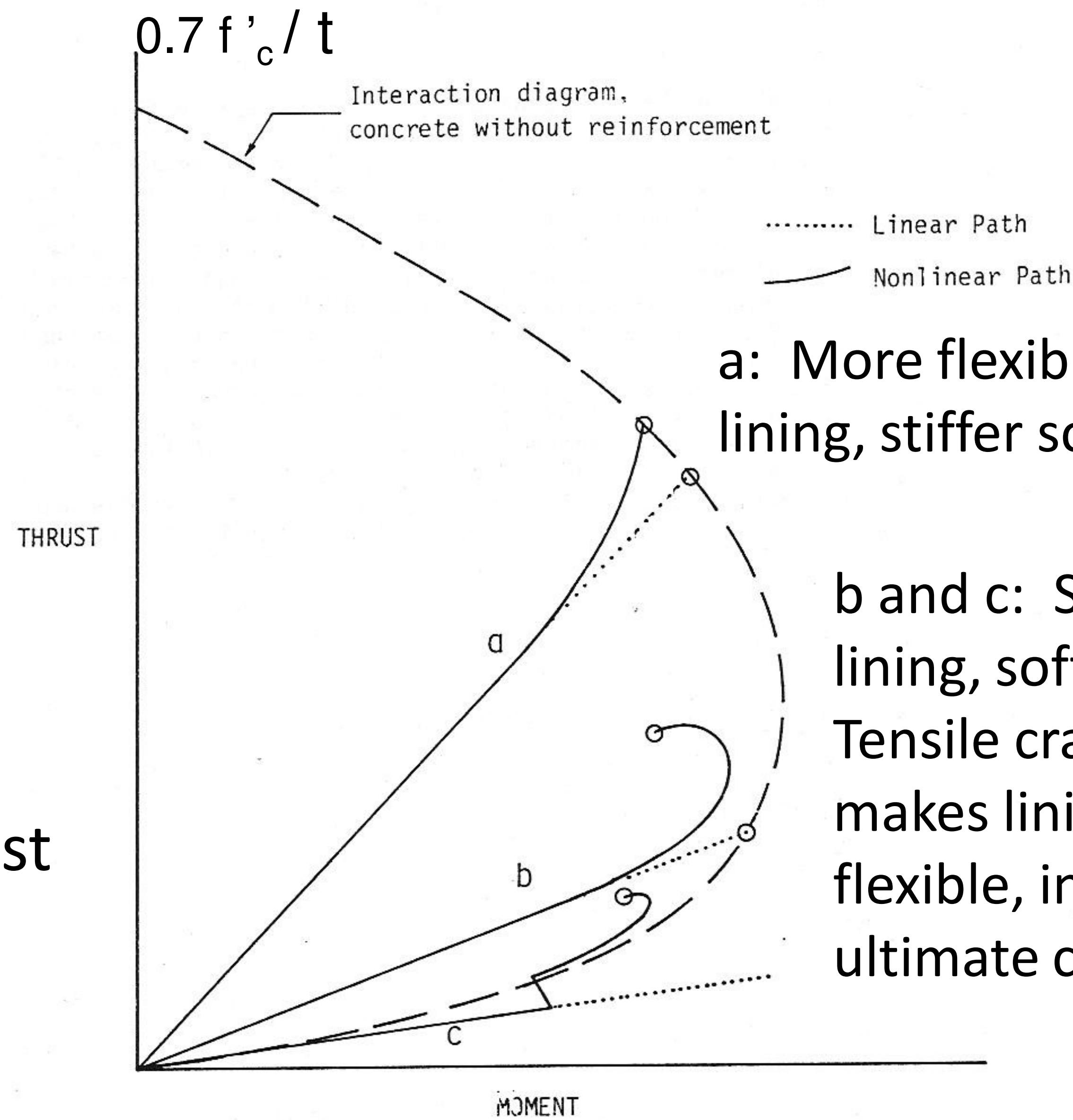
# Ultimate Capacity of Concrete Tunnel Linings
# University of Illinois: 1970's

- 10-ft-diameter
- Non-reinforced and reinforced concrete lining
- Radial hydraulic jacks to apply:




& Passive reactions
based on soil stiffness

# Results of Tests on Concrete Tunnel Linings



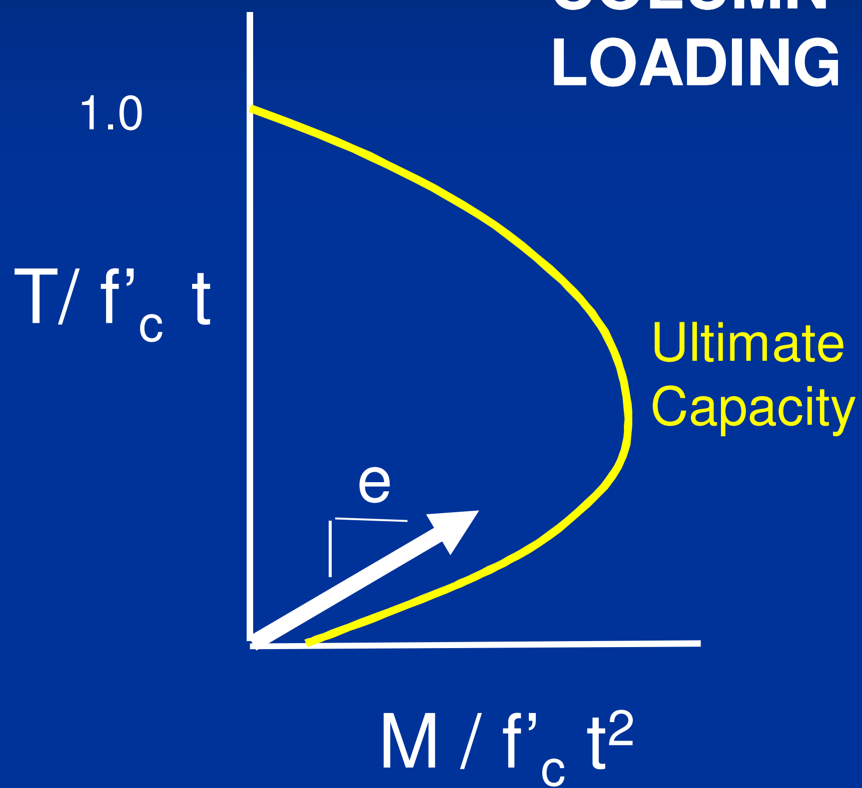

a: More flexible lining, stiffer soil

b and c: Stiffer lining, softer soil: Tensile cracking makes lining more flexible, increases ultimate capacity

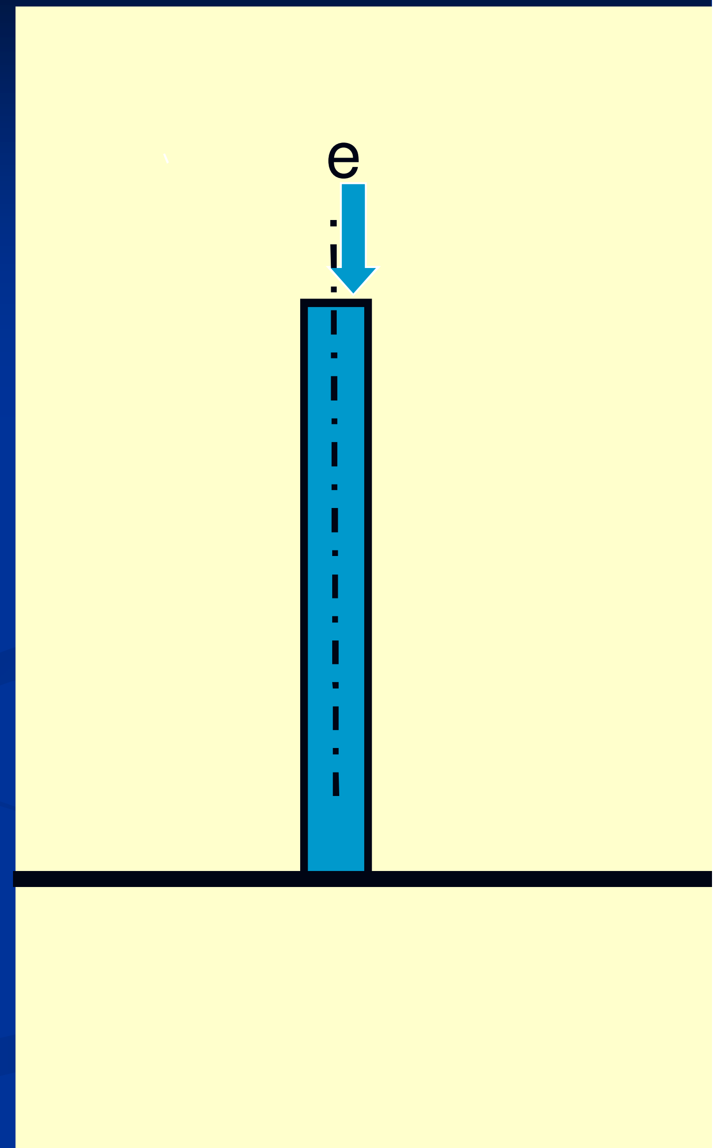
Ultimate Moment-Thrust Interaction Diagram

# BEAM-COLUMN ABOVE GROUND

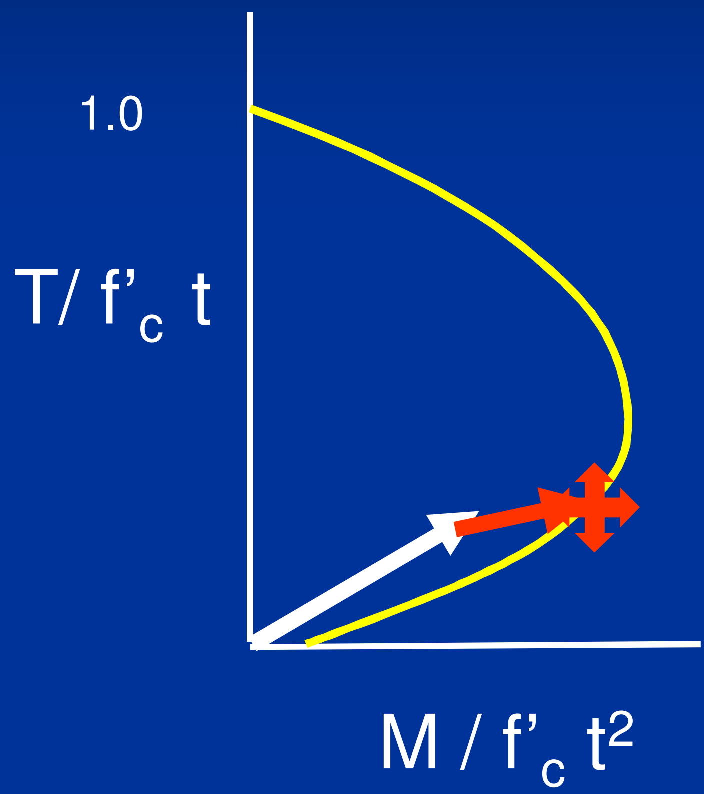
**ECCENTRIC COLUMN LOADING**



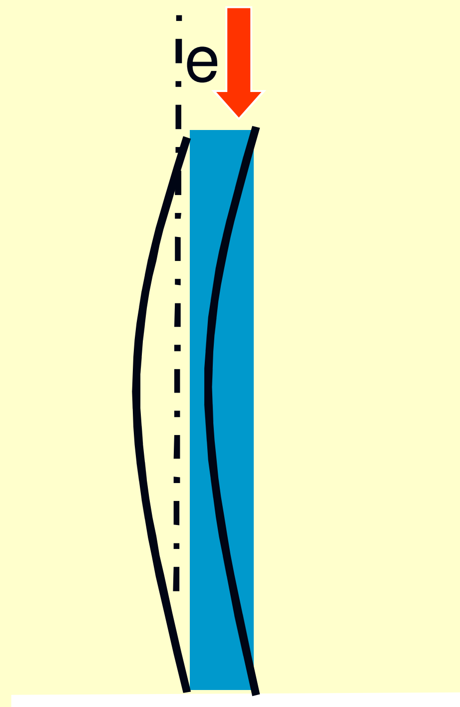

$e = M / T$



# BEAM-COLUMN ABOVE GROUND



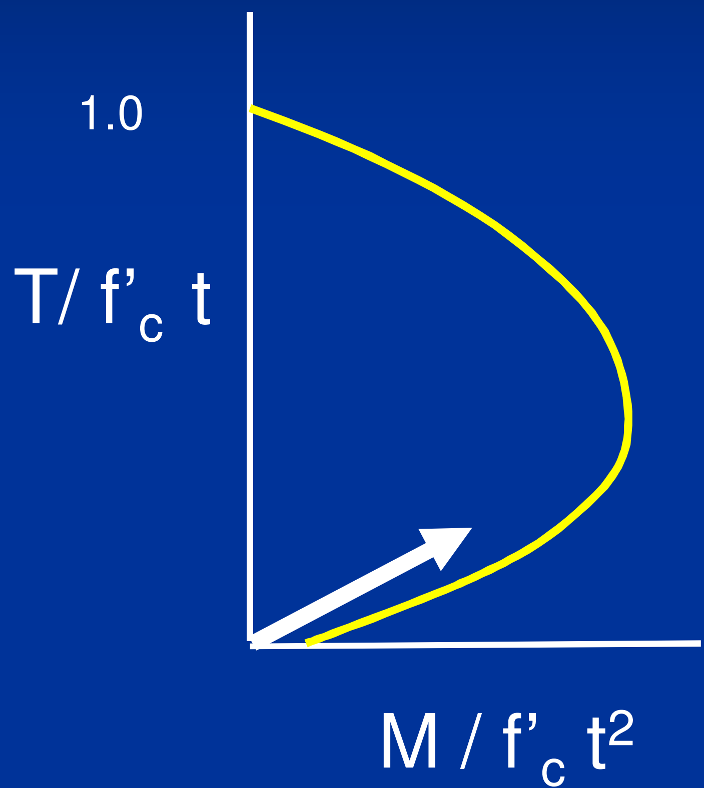

**INCREASING DEFLECTION…**

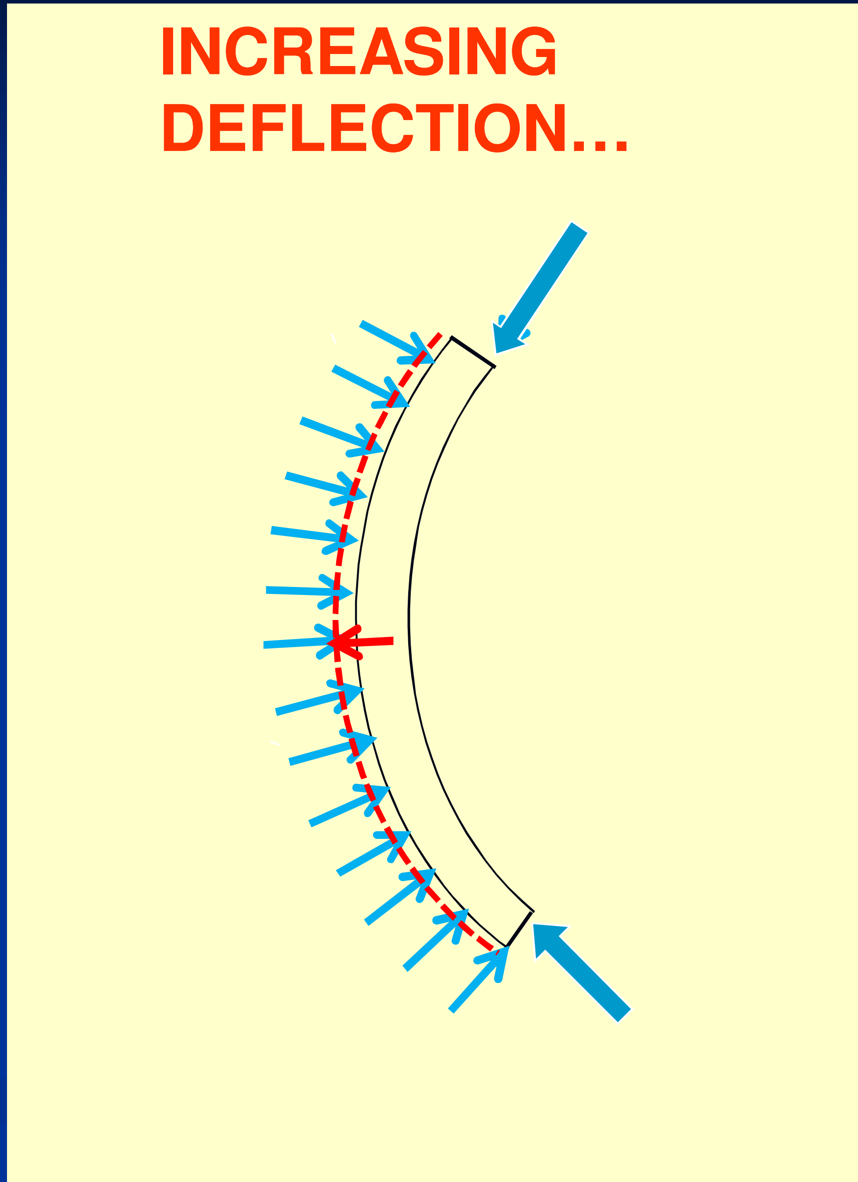



**INCREASING ECCENTRICITY …**

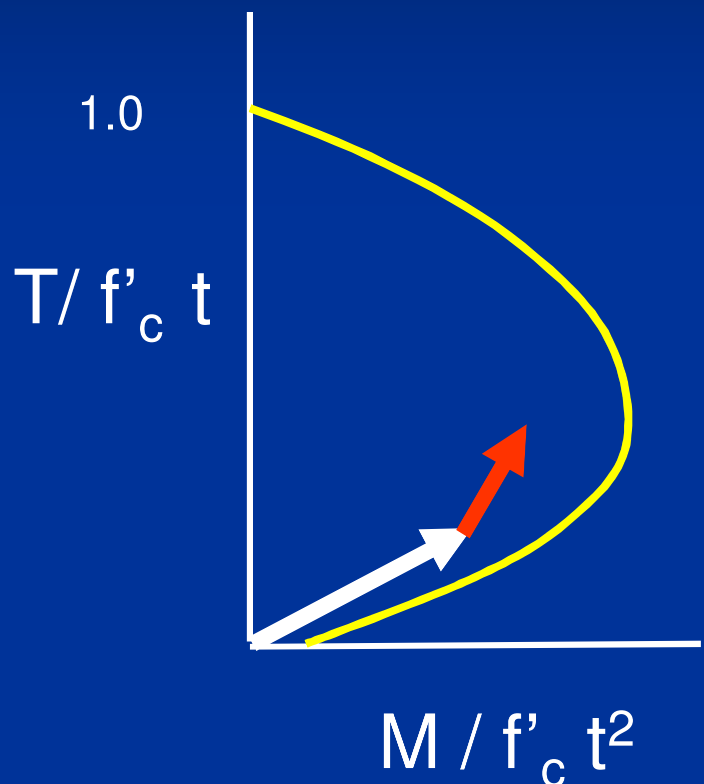
**COLUMN COLLAPSE**

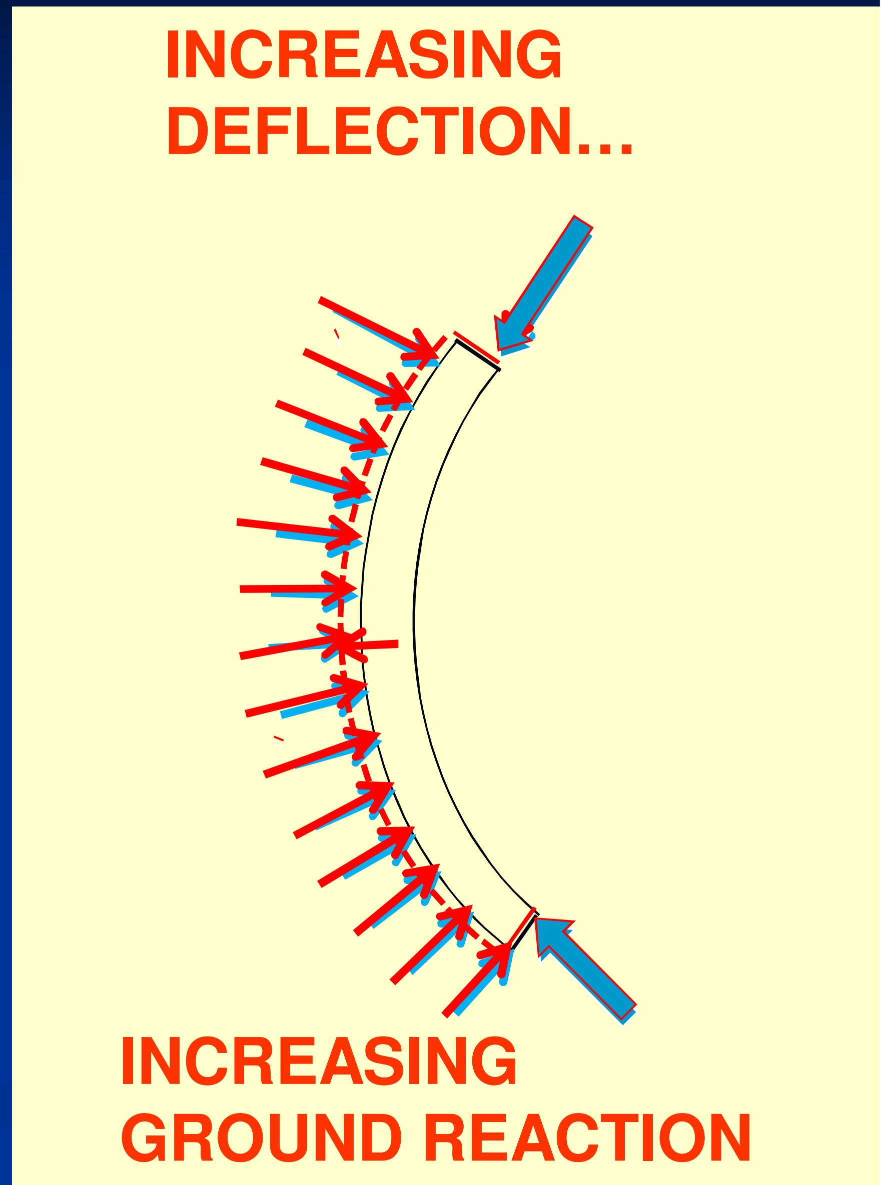
# BEAM-COLUMN IN TUNNEL



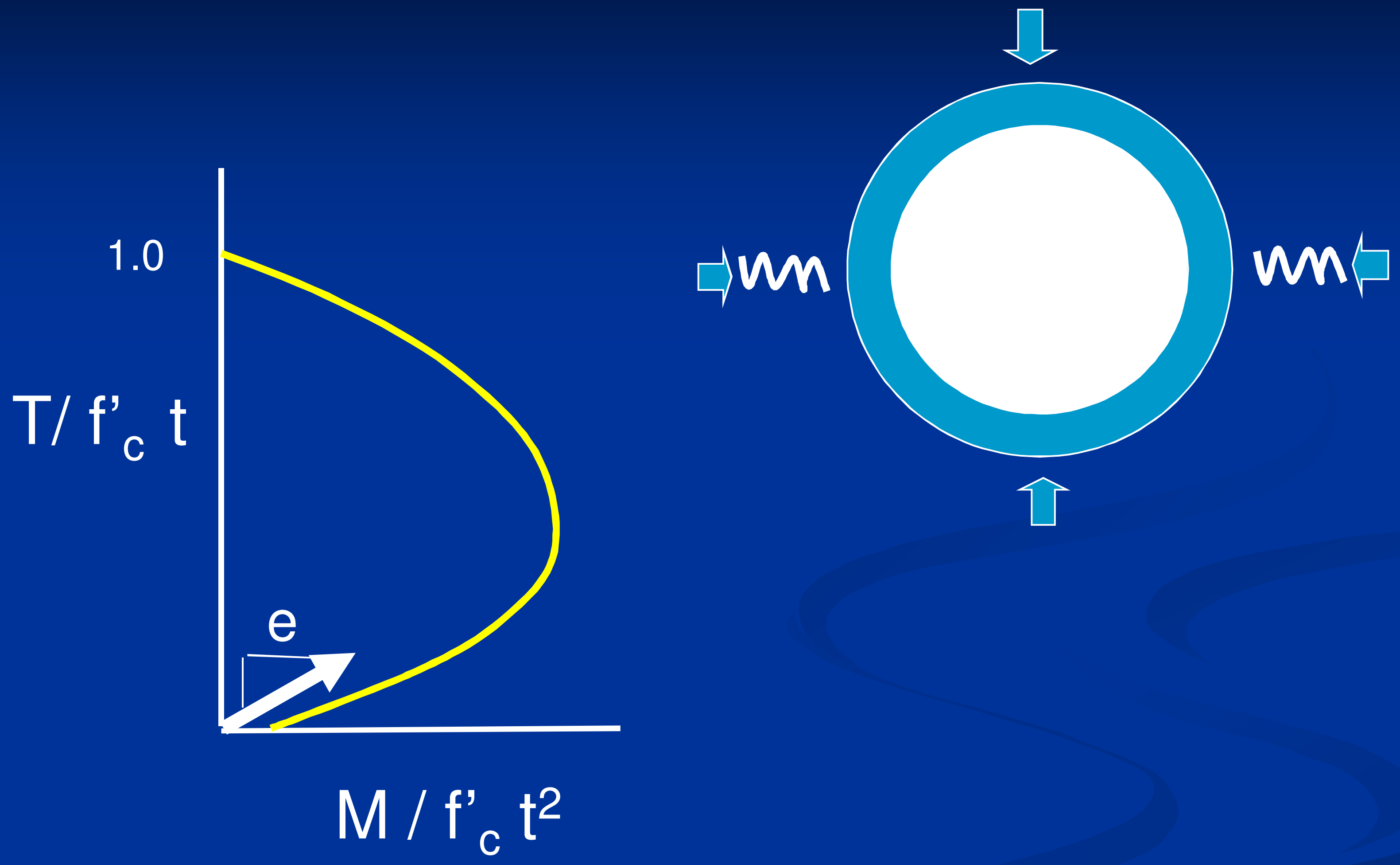



# BEAM-COLUMN IN TUNNEL

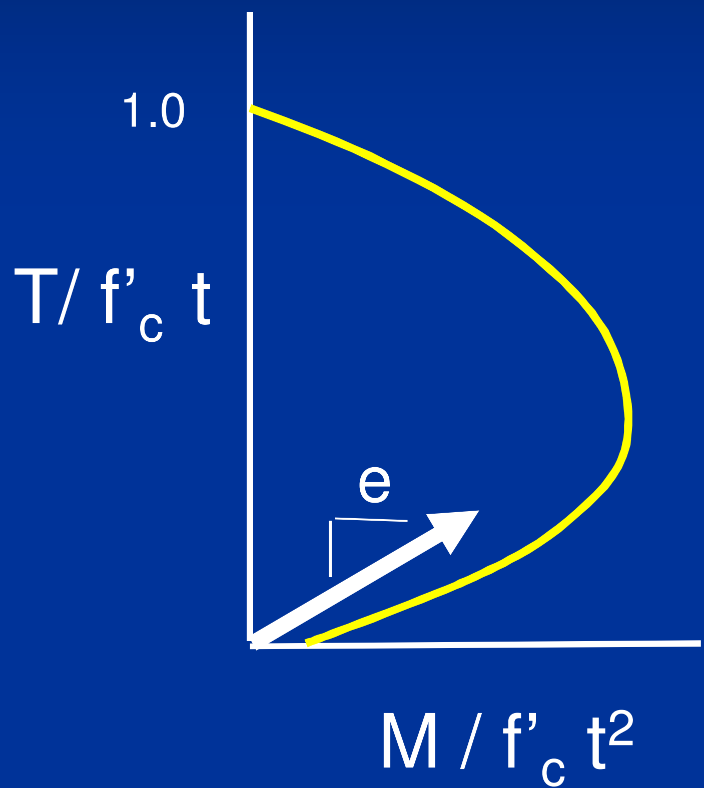


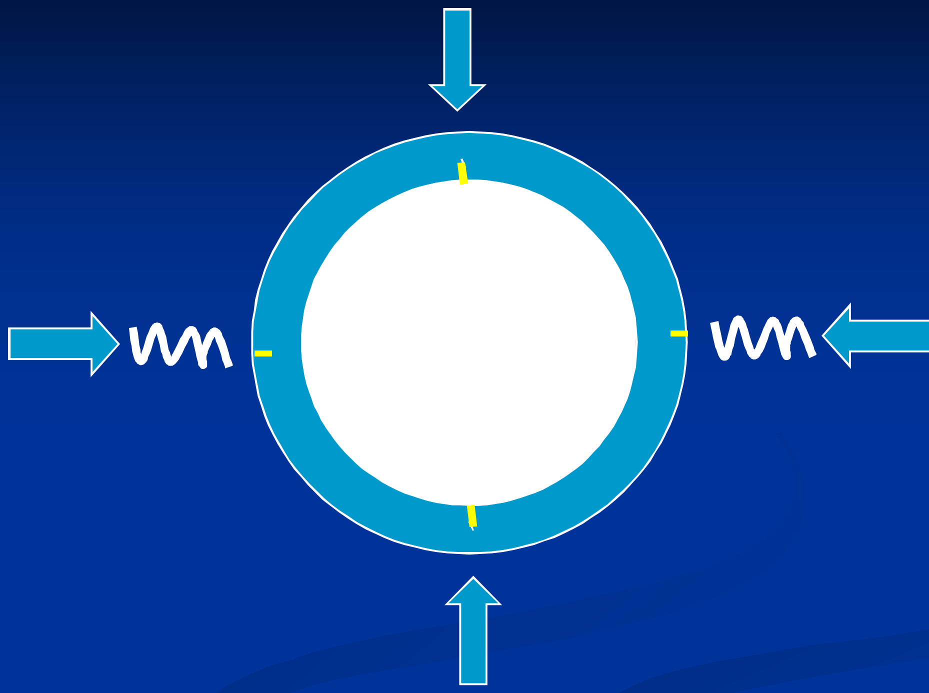



# Non-linear behavior of concrete lining

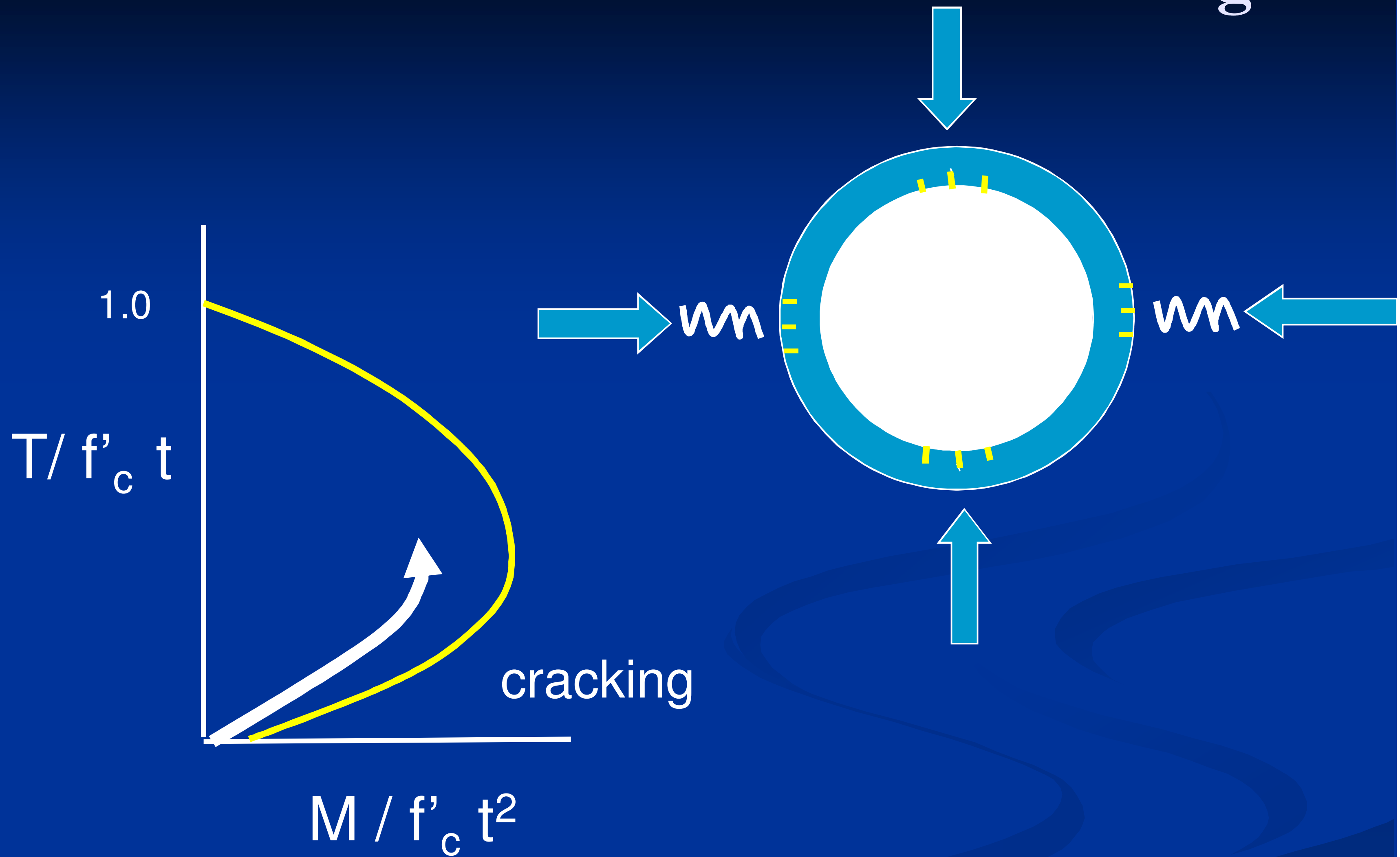


# Non-linear behavior of concrete lining



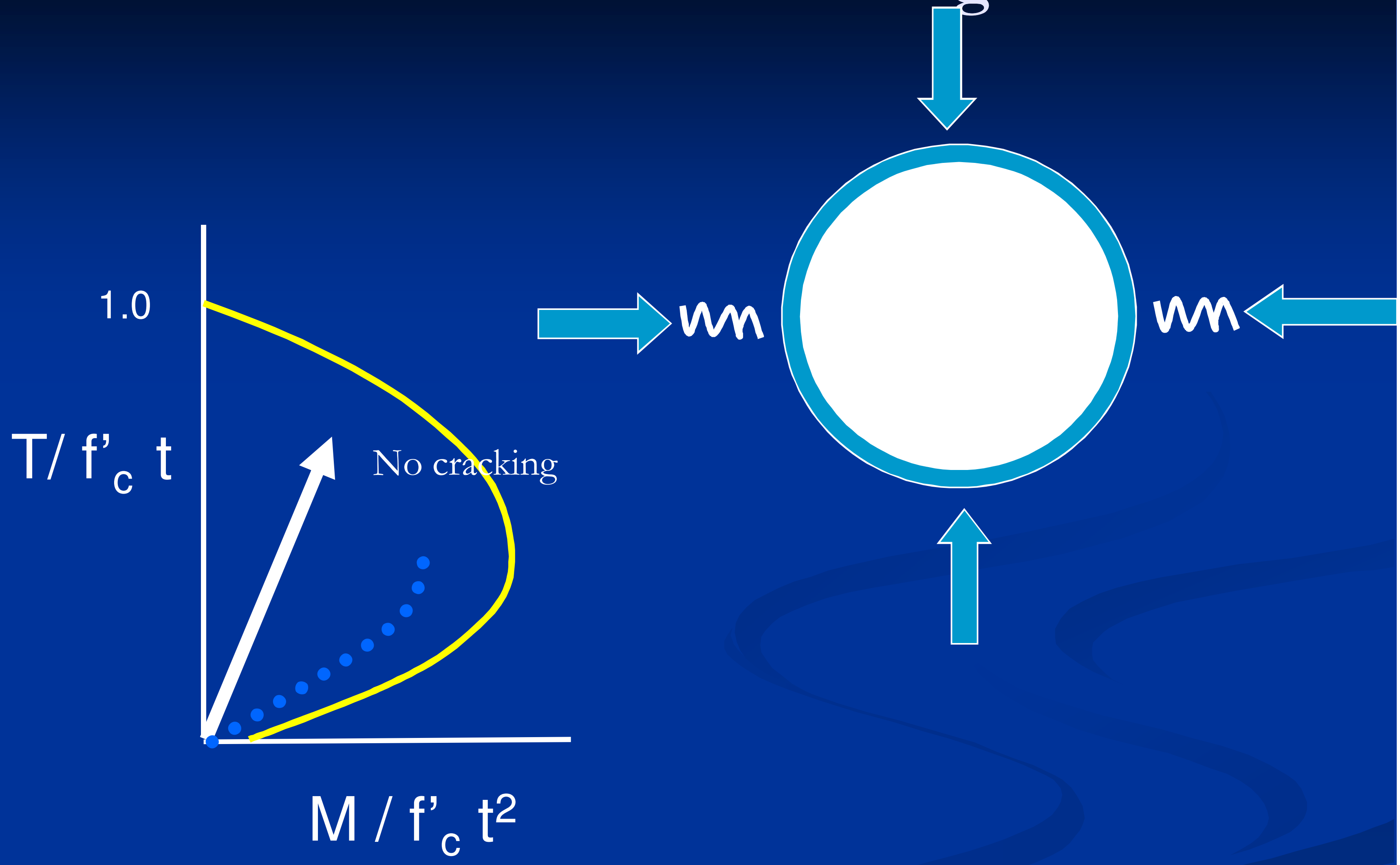



# Non-linear behavior of concrete lining




Lining becomes more flexible

# Thin concrete lining



# 3.4 Seismic Ground-Structure interaction

- Lessons learned in the last few decades in the design of underground structures to accommodate seismic ground motions.
- Designers are analyzing the ground motions imposed versus the displacement capacity of the structure
  - – rather than adding seismic loads and increasing the load capacity – and stiffness -- of the structure.

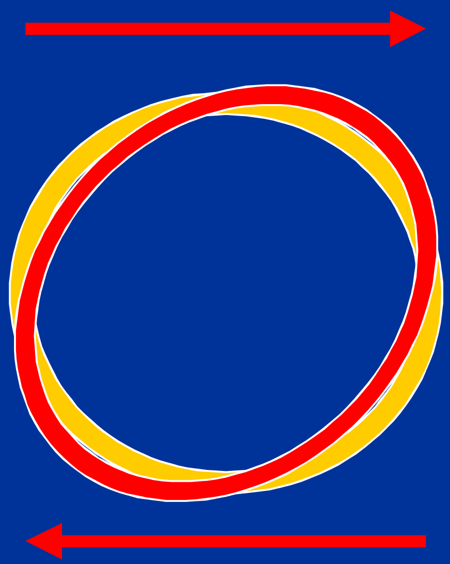
# 1994: LA METRO
# Independent Tunnel Advisory Panel:

## Are tunnels safe?

Concrete lining thickness
and quality

Seismic ground motions

# 1994: LA METRO
# Independent Tunnel Advisory Panel:

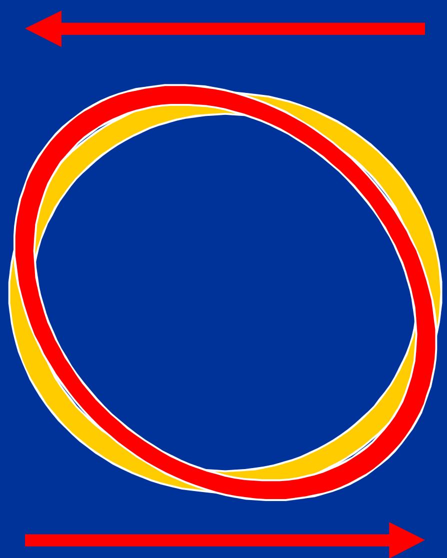


## Are tunnels safe?

Concrete lining thickness
and quality

Seismic ground motions

# 1994: LA METRO
# Independent Tunnel Advisory Panel:



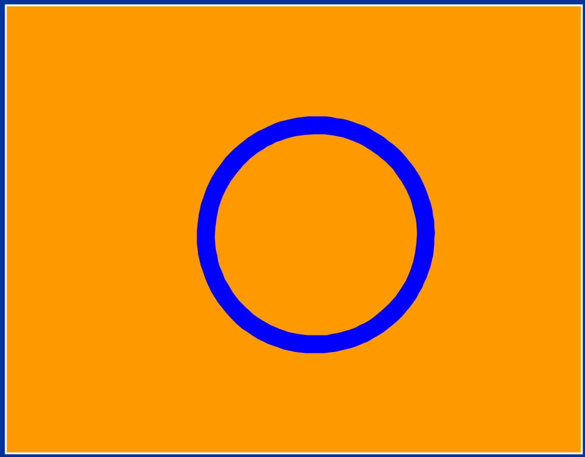
## Are tunnels safe?

Concrete lining thickness
and quality

Seismic ground motions

# Earthquake loads or ground motions ?

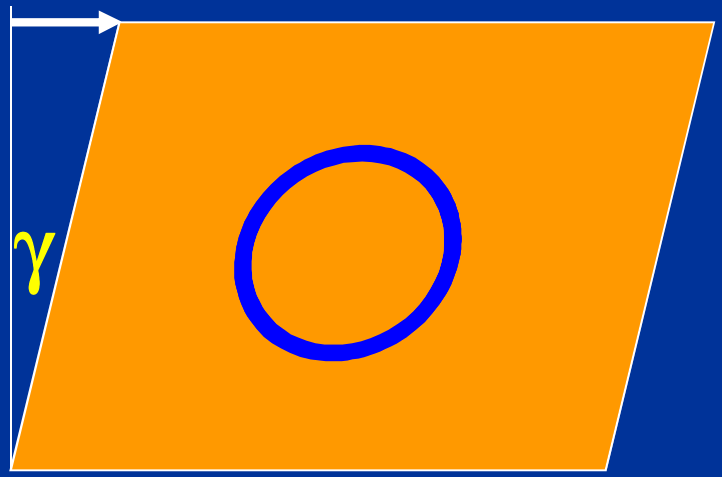
- Ground motions are imposed on the tunnel, and the tunnel must largely move with the ground.



# Earthquake loads or ground motions ?

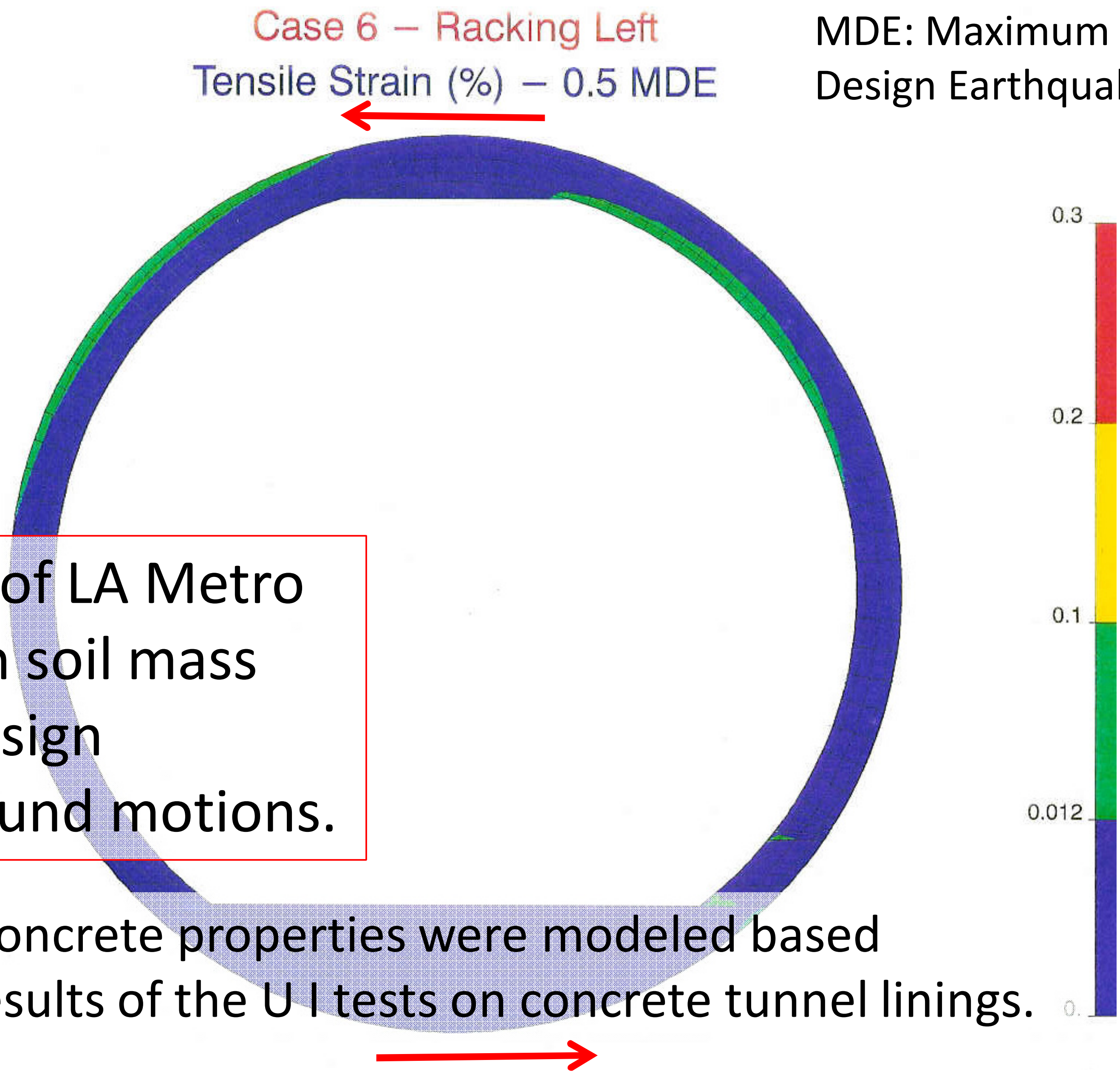
- Ground motions are imposed on the tunnel, and the tunnel must largely move with the ground.

$\gamma = \boldsymbol{Vs / Cs}$




- Compare shear displacements imposed to the displacement capacity of the lining

MDE: Maximum Design Earthquake

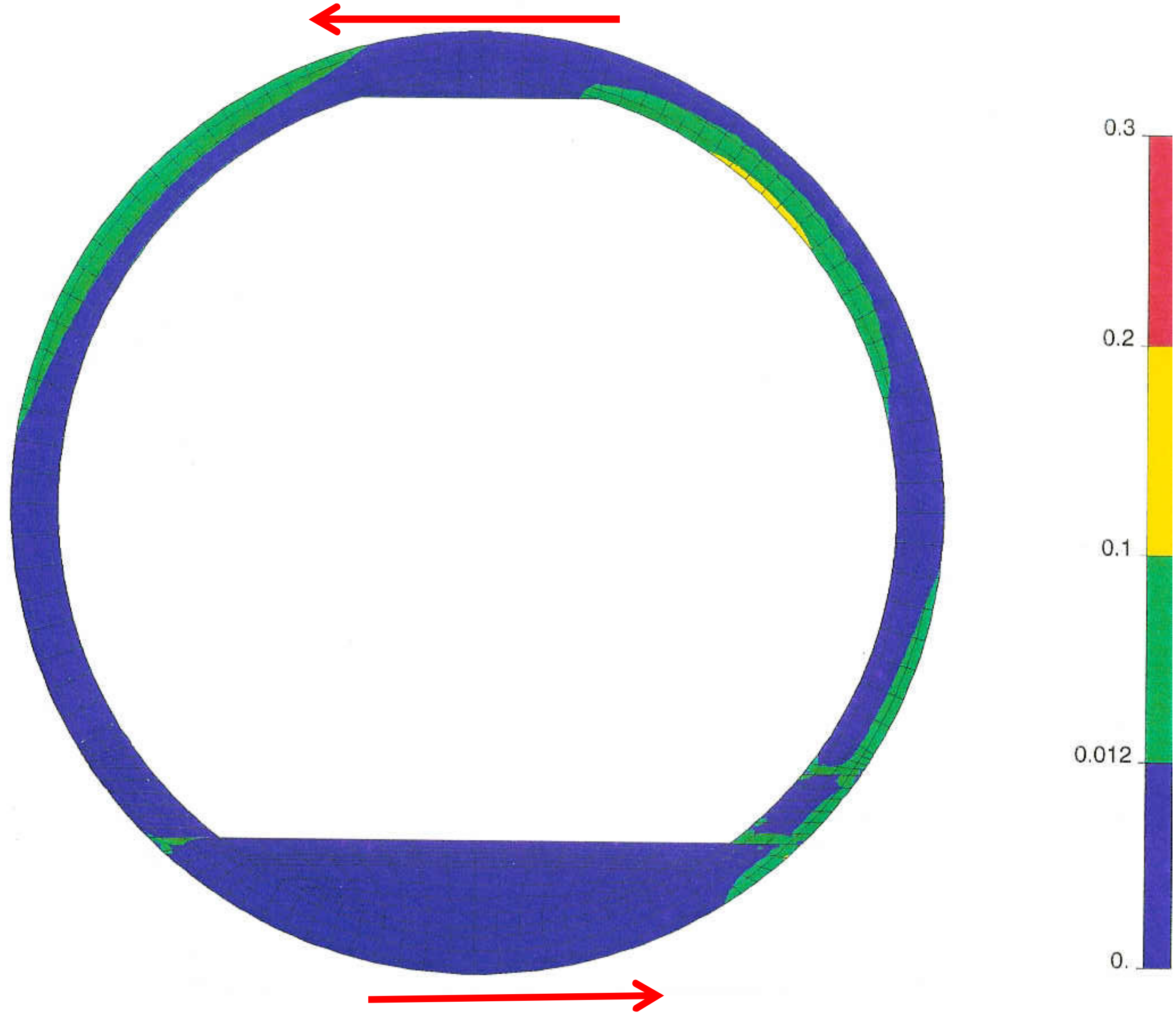



1994: Analysis of LA Metro tunnel linings in soil mass subjected to design earthquake ground motions.

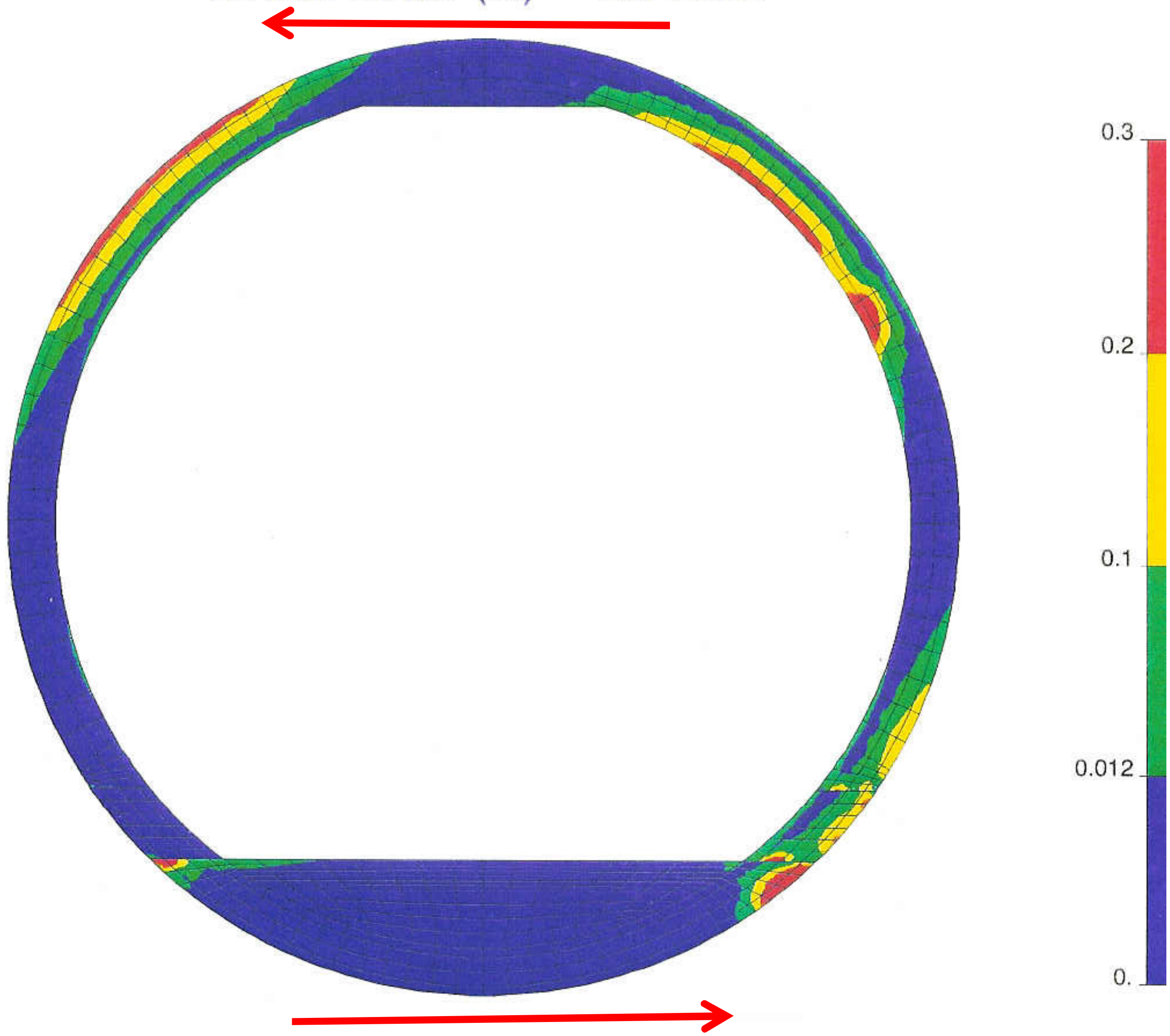
Non-linear concrete properties were modeled based on results of the U I tests on concrete tunnel linings.

# Case 6 – Racking Left

## Tensile Strain (%) – 1.0 MDE



## Tensile Strain (%) – 2.0 MDE

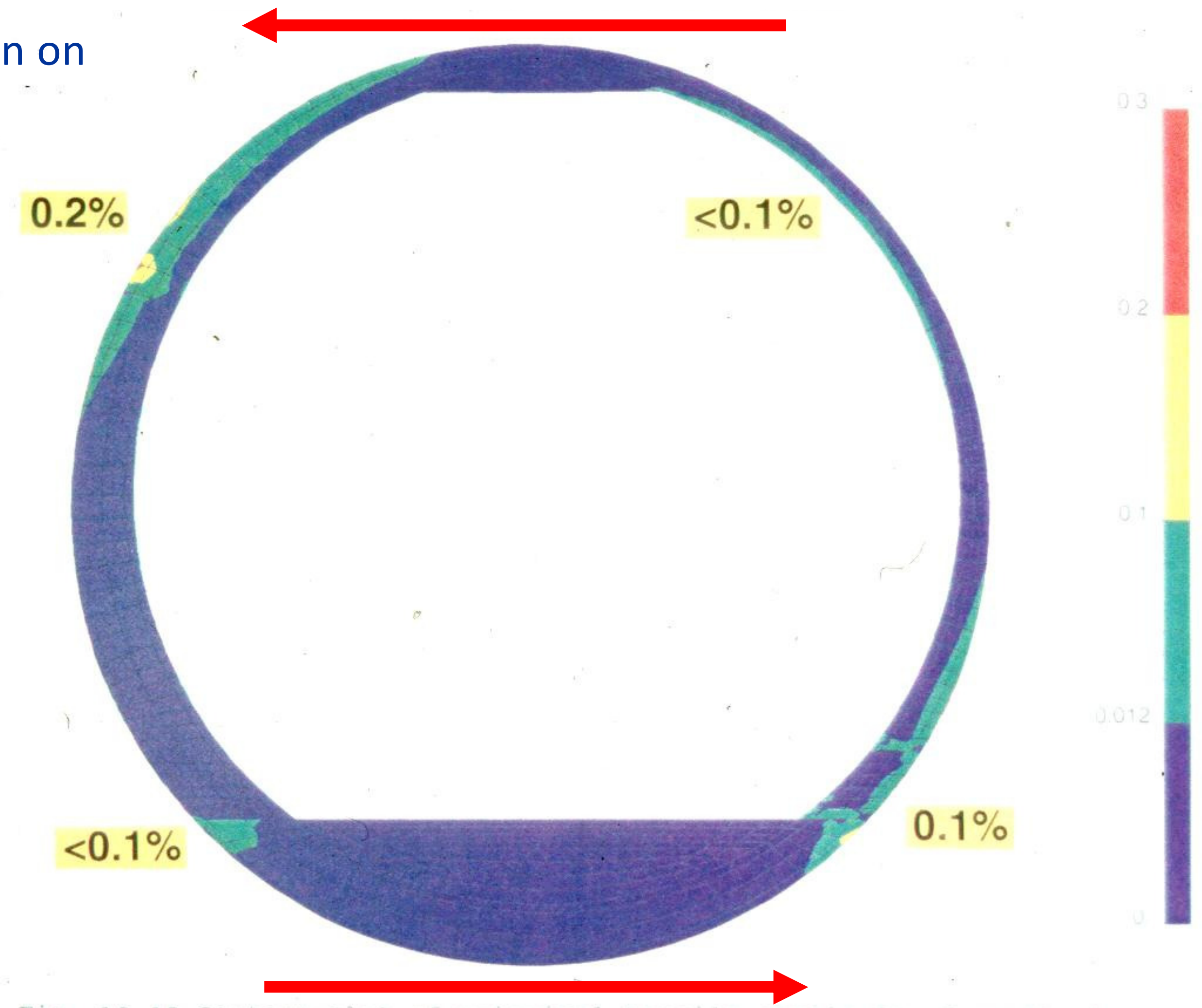


# THICK LINING ON LEFT, THIN ON RIGHT

## % Tensile Strains: 1.0 Max. Design Earthquake

## (LEFT)

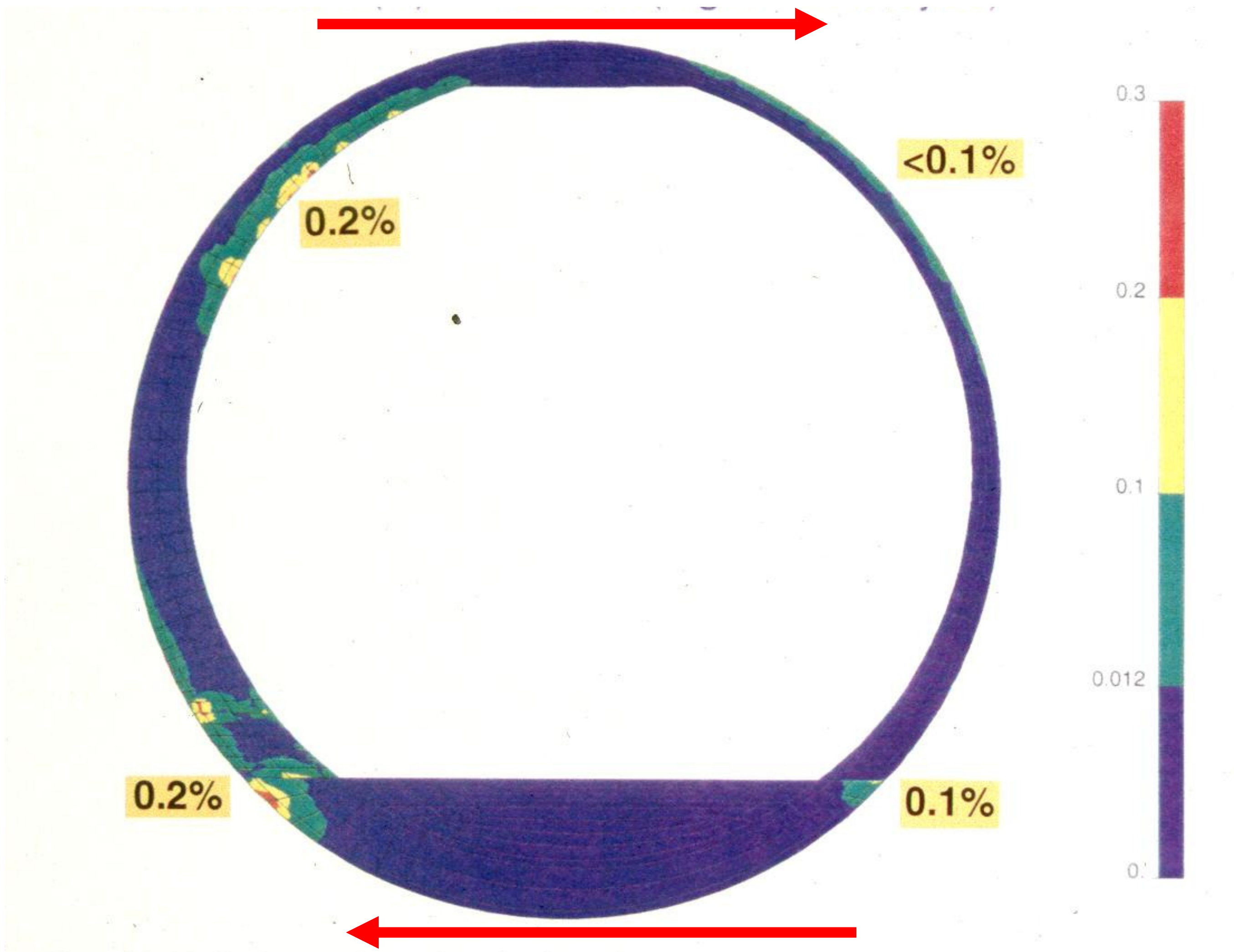
Higher strain on thicker side



# THICK LINING ON LEFT, THIN ON RIGHT

## % Tensile Strains: 1.0 Max. Design Earthquake

## (RIGHT)



# Findings from Racking Analyses

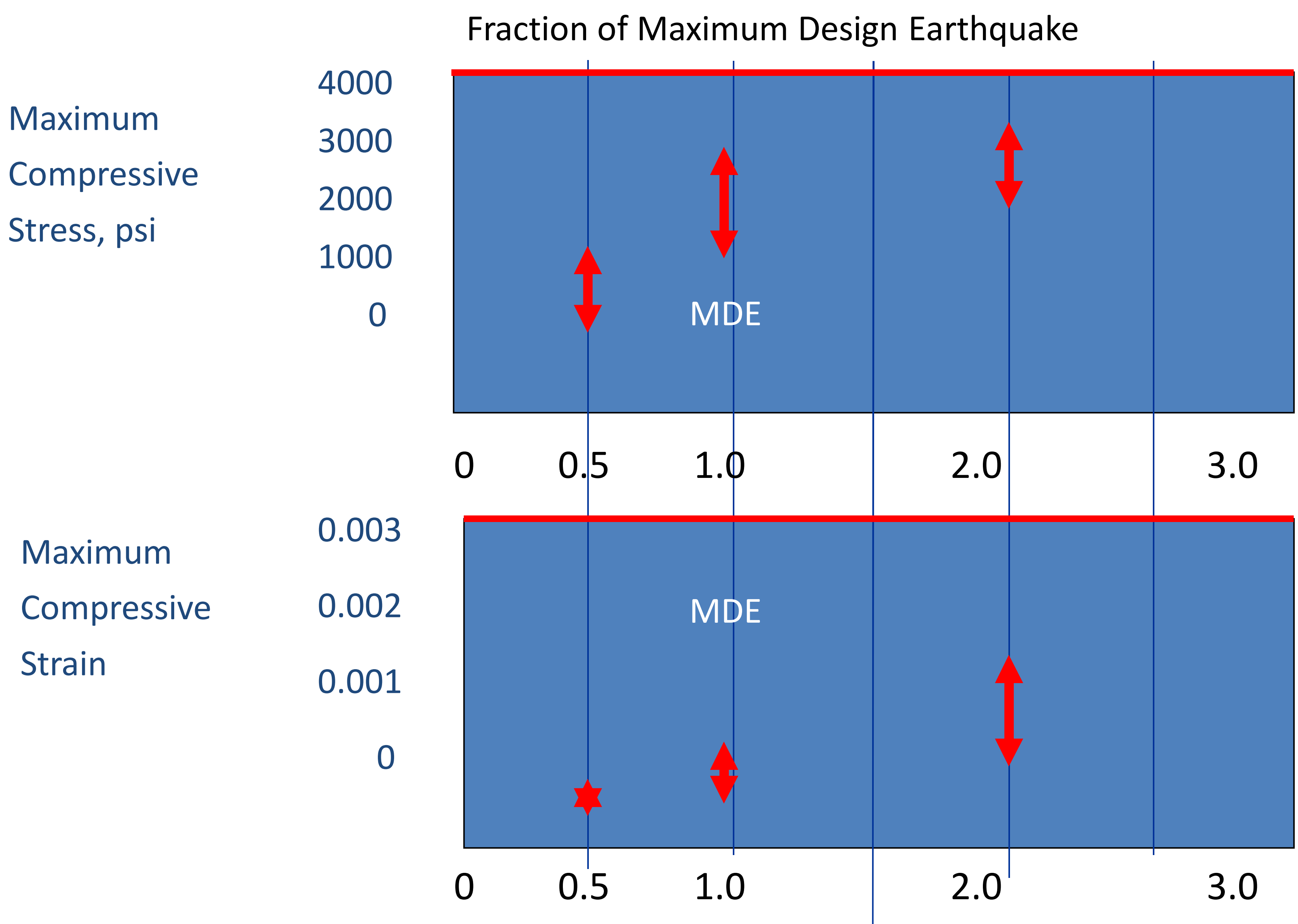
- Lining thicknesses ranging from 6 to 18 in. were capable of accepting displacements well in excess of MDE without crushing
  - 3 to 5 times MDE displacement.

- Thicker linings are subject to higher tensile strains & cracking

- Tensile cracking reduces stiffness (EI) of lining section.
  - …and significantly increases lining displacement capacity from that determined using elasto-plastic assumptions for a constant stiffness lining with no tension cracks.
  - (Constant stiffness lining, with no tension cracks, is forced to fail in compression at lower strain levels. Such a result would be obtained if the lining is heavily over-reinforced.)

- Stiffness contrasts cause concentration of cracks.

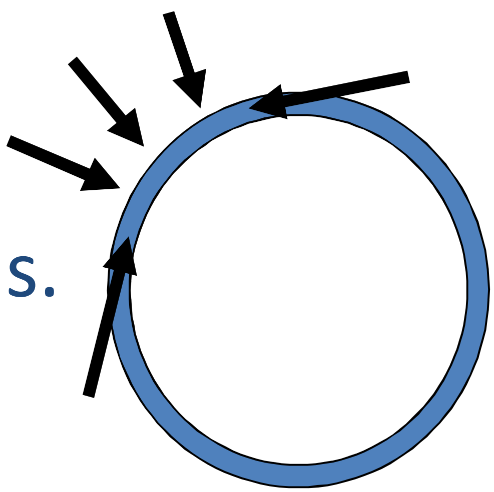
# LINING CAPACITY




18 cases: varying geometry and stiffness

# Design and construction of tunnel linings
# … for static loads and interaction
# … and for dynamic ground motions

- Tunnel  arches work because of the reaction provided by the ground.
- This is true for both static loads & earthquake-induced ground motions.



- Focus on designing and building arches in good contact with the ground.
  …Grouting

# 3.5 Lessons learned on ground-structure interaction

More lessons need to be learned on ground-structure interaction.

On major underground cavern designs, the requirement to sum all effects on the structure as factored loads can result in a loss of perspective regarding:

- the loads that need to be carried to maintain stability
- the loads that are displacement controlled, dependent on the relative lining/rock stiffness.

# Lessons on ground-structure interaction need to be interdisciplinary

Even today, there are cases where the interaction between the ground and the structure is not fully considered because of a lack of interaction between the geotechnical and the structural engineers investigating and designing the tunnel project.

# Lessons on Behavior of Tunnel Ground

*Lessons on tunnel ground behavior are learned*

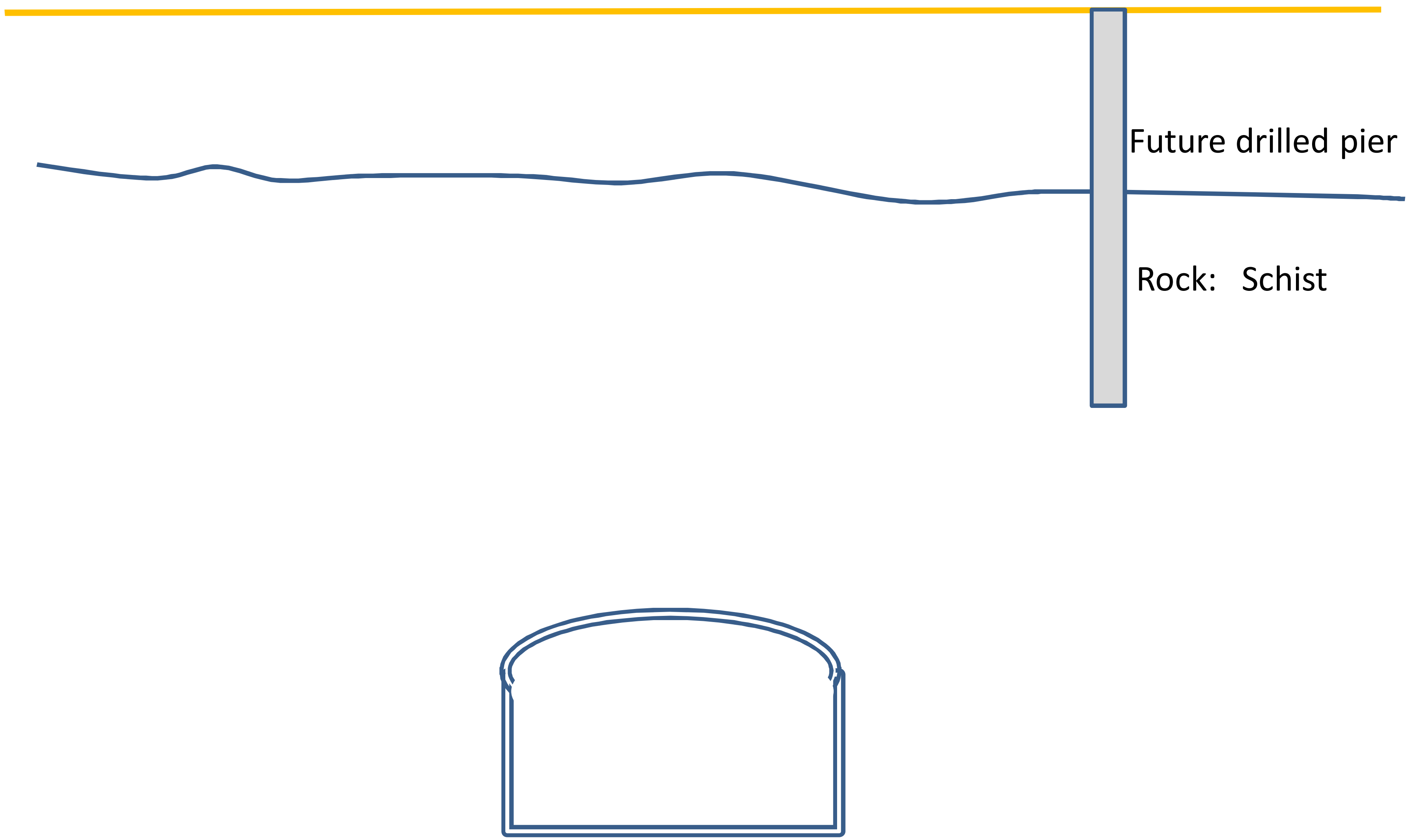
- *from the past: precedents*
- *from current tunneling technology:*
  *monitoring of ground behavior integrated*
  *with construction, machine performance*

Lessons need to be interdisciplinary:

Geotechnical interaction with

1. Geology
2. Construction
3. Structures

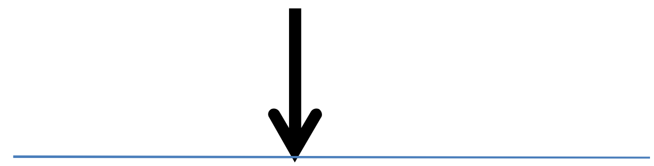
*Interaction in all three categories is critical for a successful tunnel project.*


Future drilled pier
Rock:   Schist

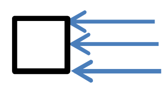
# Geotechnical Group:

Provide initial estimate of lateral loads on the tunnel wall from drilled pier:

Point Load
From drilled pier foundation



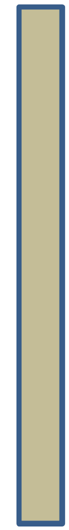
Use Boussinesq analysis to determine lateral stresses in the medium due to a point load.

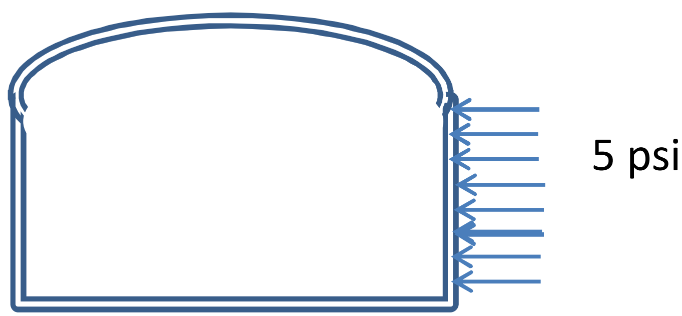


5 psi

## Structural Group:

Use the pressures given by Geotechnical Group to evaluate bending of concrete wall



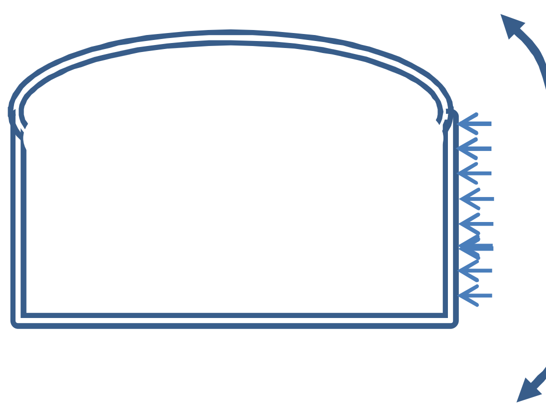



Conclusion:   Based on this initial estimate, additional reinforcement may be required.  Since this was an approximate analysis,  conduct a 3-D analysis to confirm.

Conclusion was reached without considering ground / structure interaction

Even simple closed elastic solutions would allow an estimate to be made of how ground/structure interaction would reduce loads on the structure

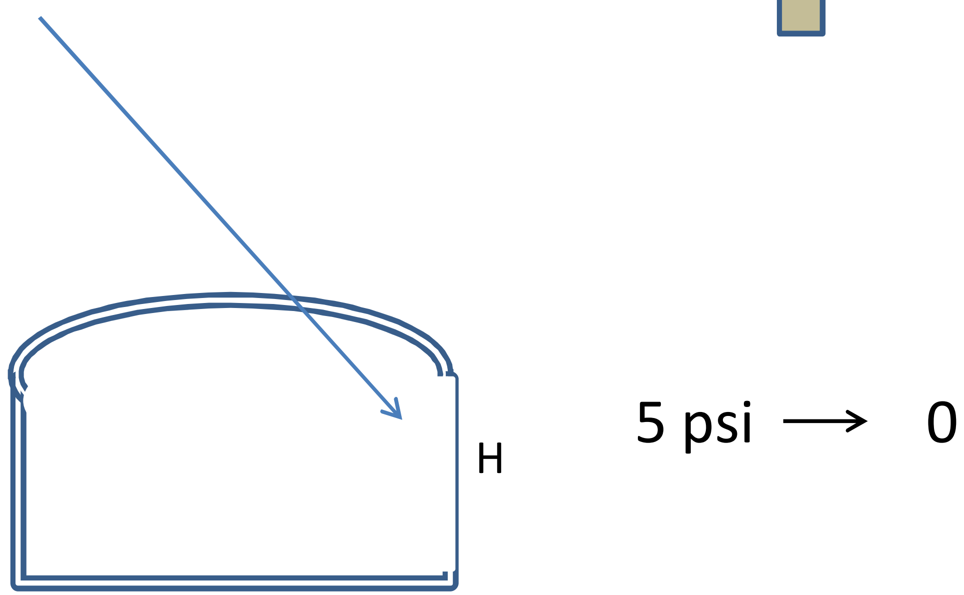
Wall is more flexible than the rock mass

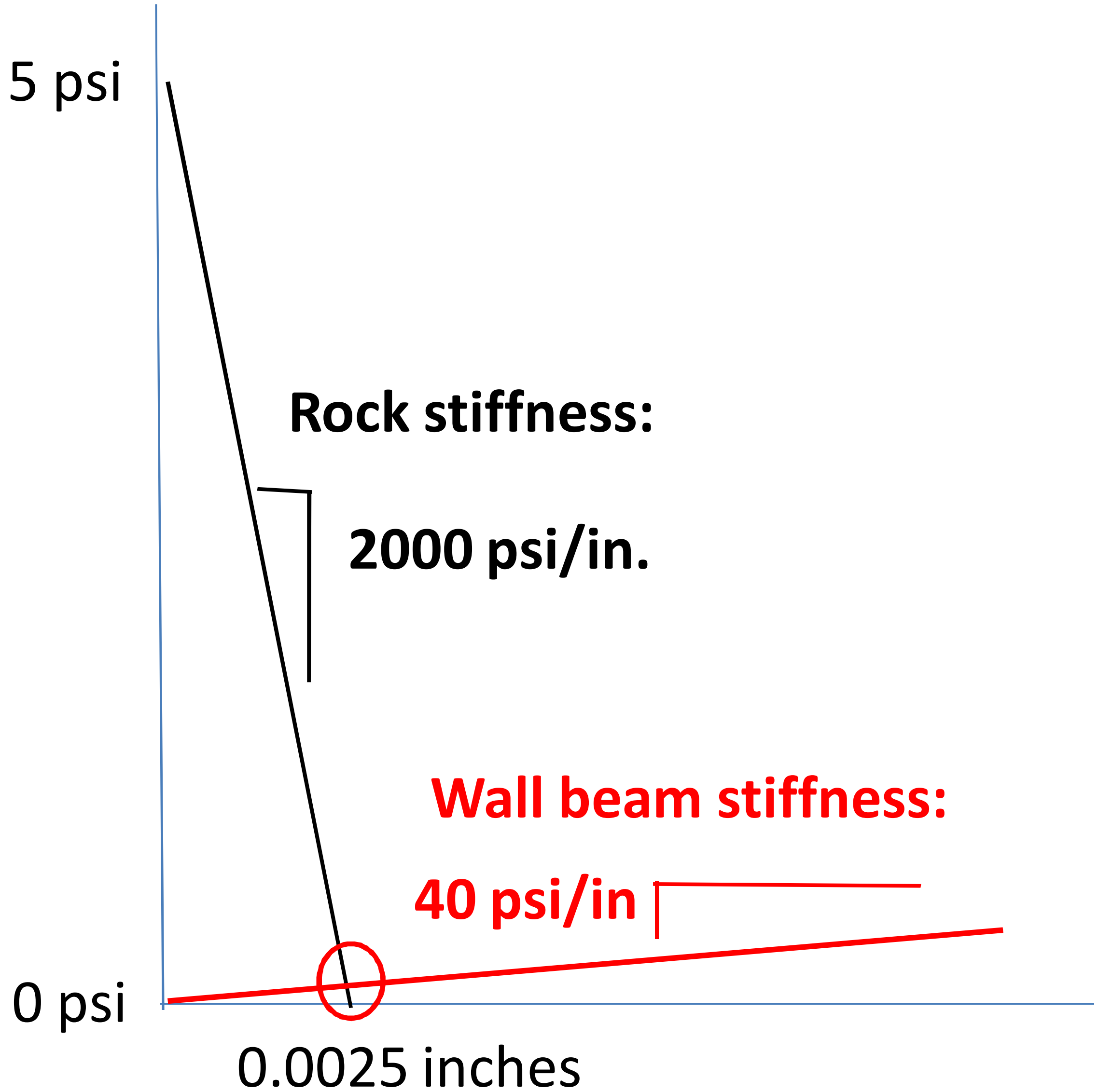


Stresses will redistribute in rock mass and stresses on wall will be < < 5 psi

Estimate displacement to relieve the calculated Boussinesq pressure

displacement ~ 0.0025 inches.






Wall deflection of 0.0025 inches will reduce pressures on concrete wall to very low values.

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