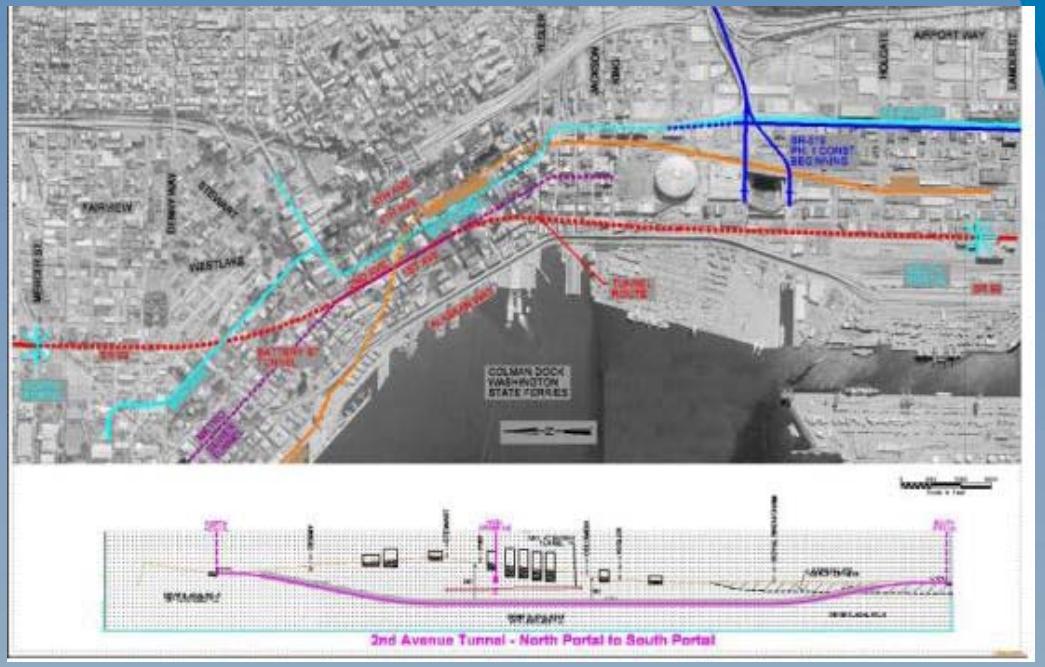
Settlement Control

- Objectives
- Engineering Analyses
- Sources of Volume Loss
- Instrumentation
- Mitigation Measures

Objectives

- Minimize impacts due to tunneling:
  - Surface settlement
  - Structure cracks and deflection
  - Buried utilities

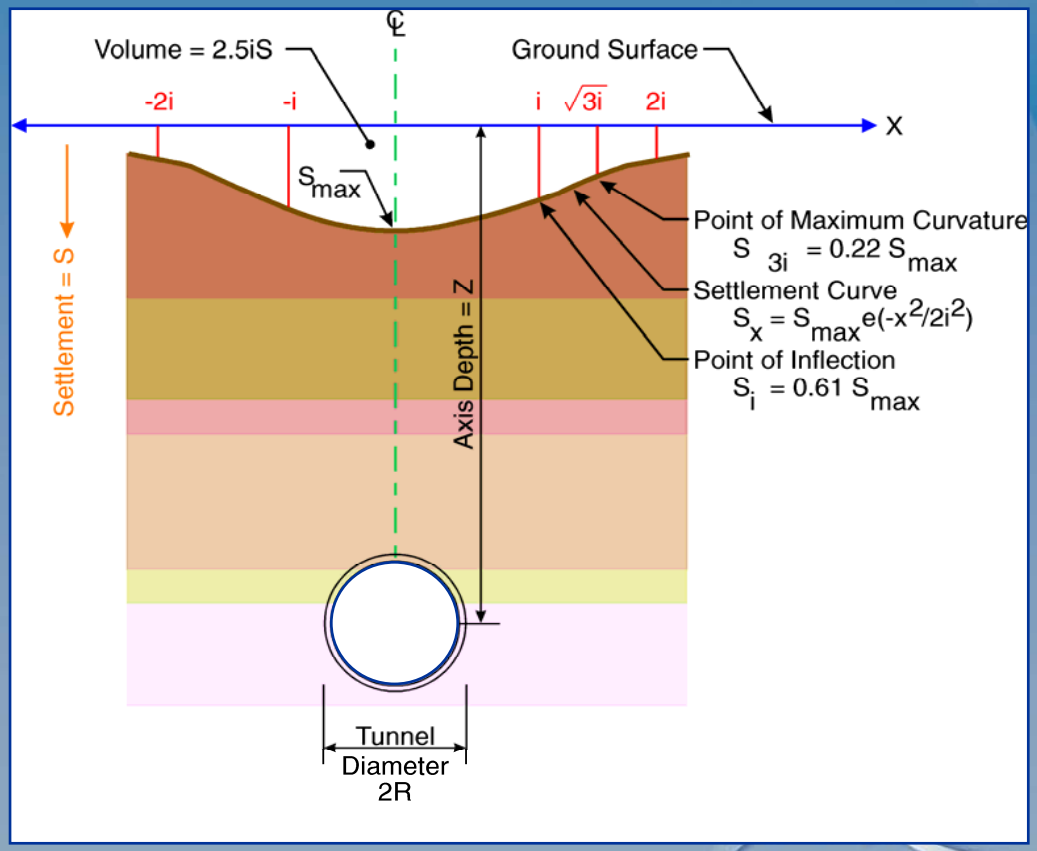


Engineering Analyses

- Ground Characterization
- Volume Loss, V_L at tunnel depth
- Settlement Trough at surface
- Condition Assessments
- Effects on Structures

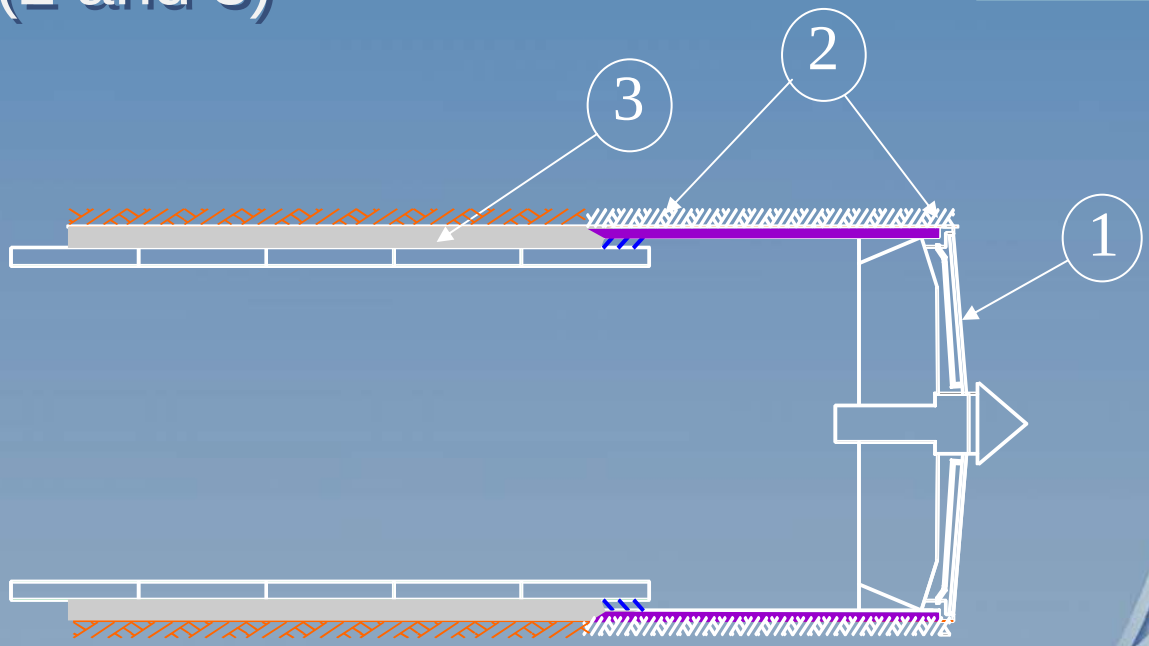
Settlement Trough

- Volume loss
  - Will transfer to the surface
  - Well established equation for settlement trough



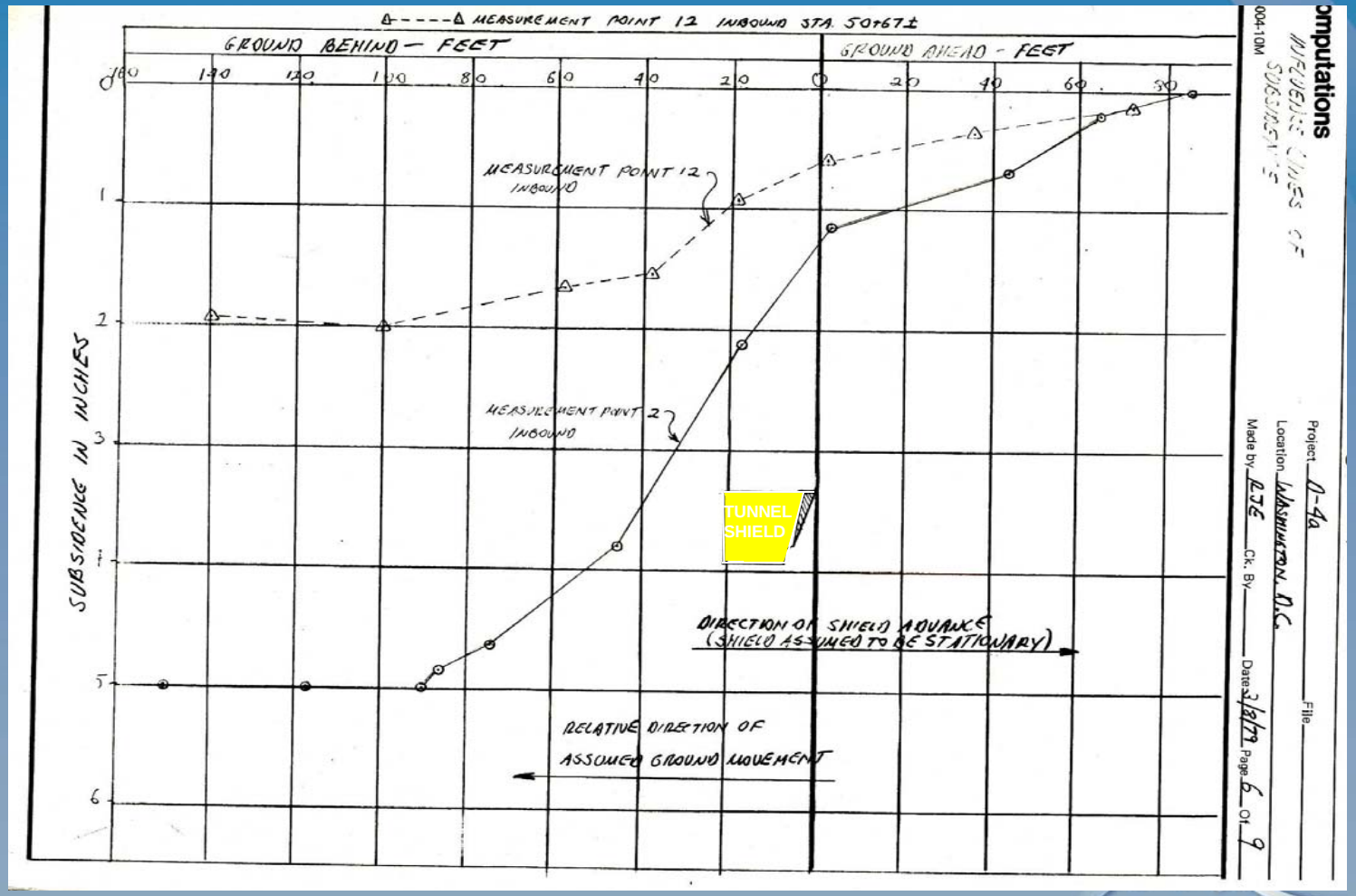
Sources of V_L during Tunneling

- Loss Through Face (1)
- Excessive Overcut for Steering (2)
- Filling of the Tail Void (3)
- Plowing (2 and 3)



D. C. Metro - 1979

- Influence lines of subsidence – open face shields



Volume Loss Magnitudes

Historical Standards	Volume Loss, V_L
■ Good practice in firm ground - better soils and excellent ground control	0.5%
■ Good practice in slow raveling ground - considered good ground	1.5%
■ Fair practice - More face and tail loss	2.5%
■ Poor practice - Yet more face loss - Tail void mostly unfilled	4.0%

Volume Loss Standards

Closed-face machines with one pass linings

- New St. Clair Tunnel — Vol. Loss <1.0%
  - Below water table
  - Very soft clay

- Toronto - Sheppard Subway — Vol.Loss <0.8%
  - Below water table — Settlement <5/8 in.
  - Variable ground conditions

Effect on Structures

- Uniform settlement - no concerns
- Angular distortion - causes damage due to tensile strain
  - 1/500 - safe limit for no cracking of buildings
  - 1/150 - potential structural damage

Instrumentation

- Measurement Objectives
  - Vertical displacements
    - Surface settlement monitors
    - Deep settlement monitors
    - Structure settlement / distortion
  - Lateral displacements
    - Ground – inclinometers
    - Structures – tilt meters
  - Water level indicators
  - Relative / absolute displacements
    - Tape / Rod Extensometers
  - Temperature effects
    - Gages / thermocouples

INSTRUMENTATION - AMSTERDAM

One of the most extensive ground monitoring surveys ever attempted is now under way in Amsterdam, years before tunnelling starts for the city's metro. David Hayward reports.

On the alert for settlement

Little moves in Amsterdam these days without the team of engineers planning the city's new $985M underground metro knowing all about it. Every creak or groan from up to 1,600 city centre buildings is being continuously monitored, while ground movements 50m beneath the streets will soon be meticulously recorded every hour.

A mammoth six year settlement survey, being carried out by French monitoring specialist Soldata, has just started. And with 140,000 readings currently being fed to the computers of the city's engineers every week, the $12.5M survey is claimed to be the most extensive for any tunnelling project.

Close scrutiny of Amsterdam's infrastructure is seen as crucial in ensuring that driving the metro's twin tunnels, directly beneath the historic heart of the Dutch capital, causes minimal surface settlement. Yet, curiously, the start of tunnelling is still three years away.

"It is vital to establish, from an independent contractor, how these buildings behave naturally over the course of a full year and long before we begin tunnelling," explains Frank Kaalberg, design manager for Witteveen + Bos, Dutch consultant for metro client the Municipality of Amsterdam. "Our overriding aim during tunnelling is to cause no structural damage to any buildings."

To achieve this goal of negligible settlement, in a city where most old buildings are continually subsiding naturally in the weak ground at an average 1mm every year, demands the cooperation of engineers, surveyors, computer software experts and tunnelling machine manufacturers.

Kaalberg and his team are now 60% through an eight year pioneering research project to design and build an "intelligent" tunnel boring machine to drive the metro's 3.8km underground section. It will be a TBM designed to interact with, and respond to, 3D computer analysis of building and subsurface movements during tunnelling. The aim is both to predict and reduce ground settlement. Working with German TBM manufacturer Herrenknecht, the team is designing a full face EPB tunnelling machine capable of exerting minimal subsoil disturbance – and therefore minimal surface settlement (see box).

Kaalberg is confident that two $9.8M intelligent machines will be off the drawing board and in the ground ready to start the twin 5.8m finished diameter drives by the end of 2004.

It is a technical challenge that must not fail, for the possibility of causing damaging surface settlement is politically just not acceptable. City residents are well aware of the potential for disruption.

The first time metro construction was planned, early in the 1970s, tunnelling technology was much less developed and the likelihood of considerable settlement ruled out bored tunnels altogether. Unfortunately, the chosen alternative for an east-west line – forming the tunnels by sinking pneumatic caissons – demanded such widespread building demolition that it triggered riots in the streets from annoyed inhabitants. Ensuring good public relations this time, for construction of the total 9km north-south line running right beneath the city centre, is seen as a major priority.

Extremities of the line will run at grade or in cut and cover. But the central 3.8km section will be routed through twin tunnels driven at an average depth of 30m directly beneath Amsterdam's main thoroughfares lined with many of the city's most architecturally important buildings.

Four of the nine stations will be formed in large cover and cut boxes lined with diaphragm walling

Left: The central 3.8km section of the 9km metro route will run in 5.8m diameter twin tunnels driven beneath Amsterdam's main streets. Four of the nine stations will be built within large 30m deep cut and cover boxes excavated 30m deep and only metres from historic timber piled buildings.

Monitoring and Feedback

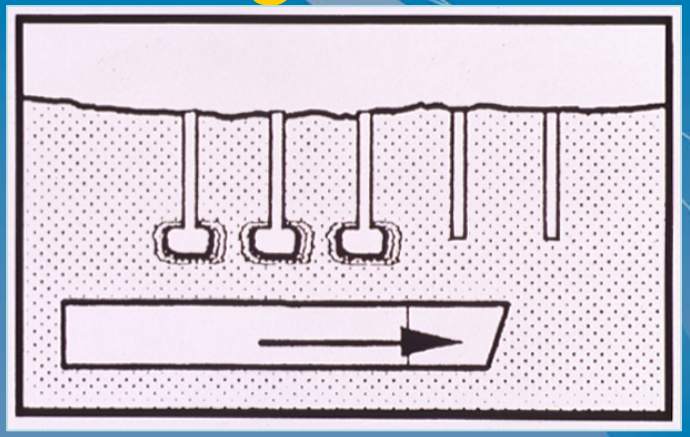
- Distant / Deep Reference Datums
- Background readings
  - Temperature
  - Seasonal
- Automated Recording Systems
  - Automatic readings
  - GIS-Based Integrated Databases
  - Real-time link to machine operators

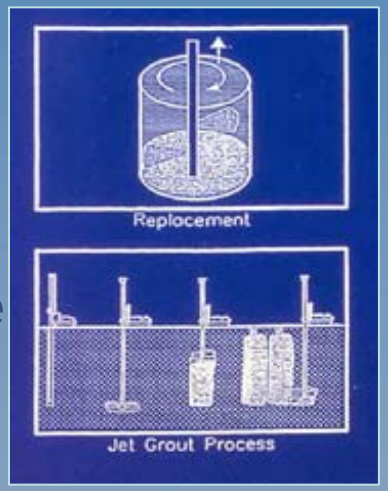
Mitigation Measures

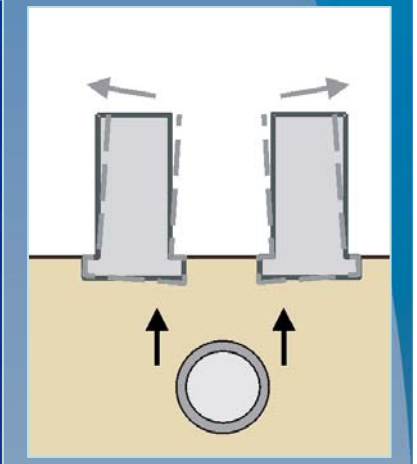
- Grouting Methods
- Freezing Methods
- Face Conditioning Agents

Mitigation Measures - Grouting

- Compaction grouting
  - Stiffen / densify soils at foundations before or following tunneling
- Jet Grouting
  - Columns of mixed grout/soil in tunnel zone before tunneling
- Compensation grouting
  - Fracture-grout to strengthen soil before and to lift ground during tunneling - between tunnels and areas of concern







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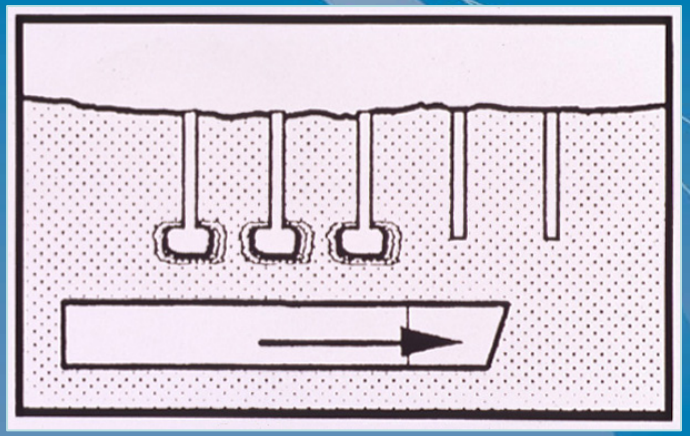
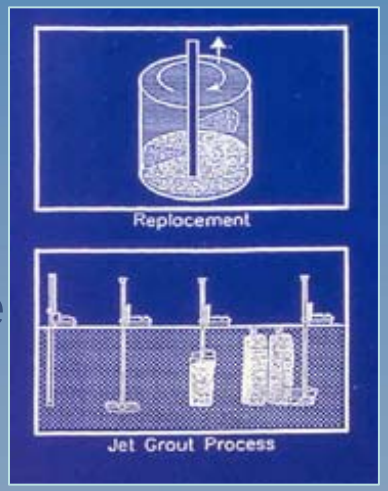
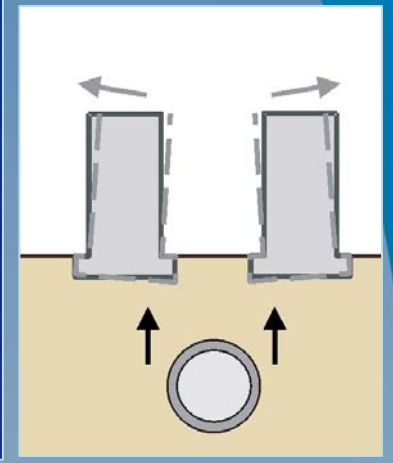






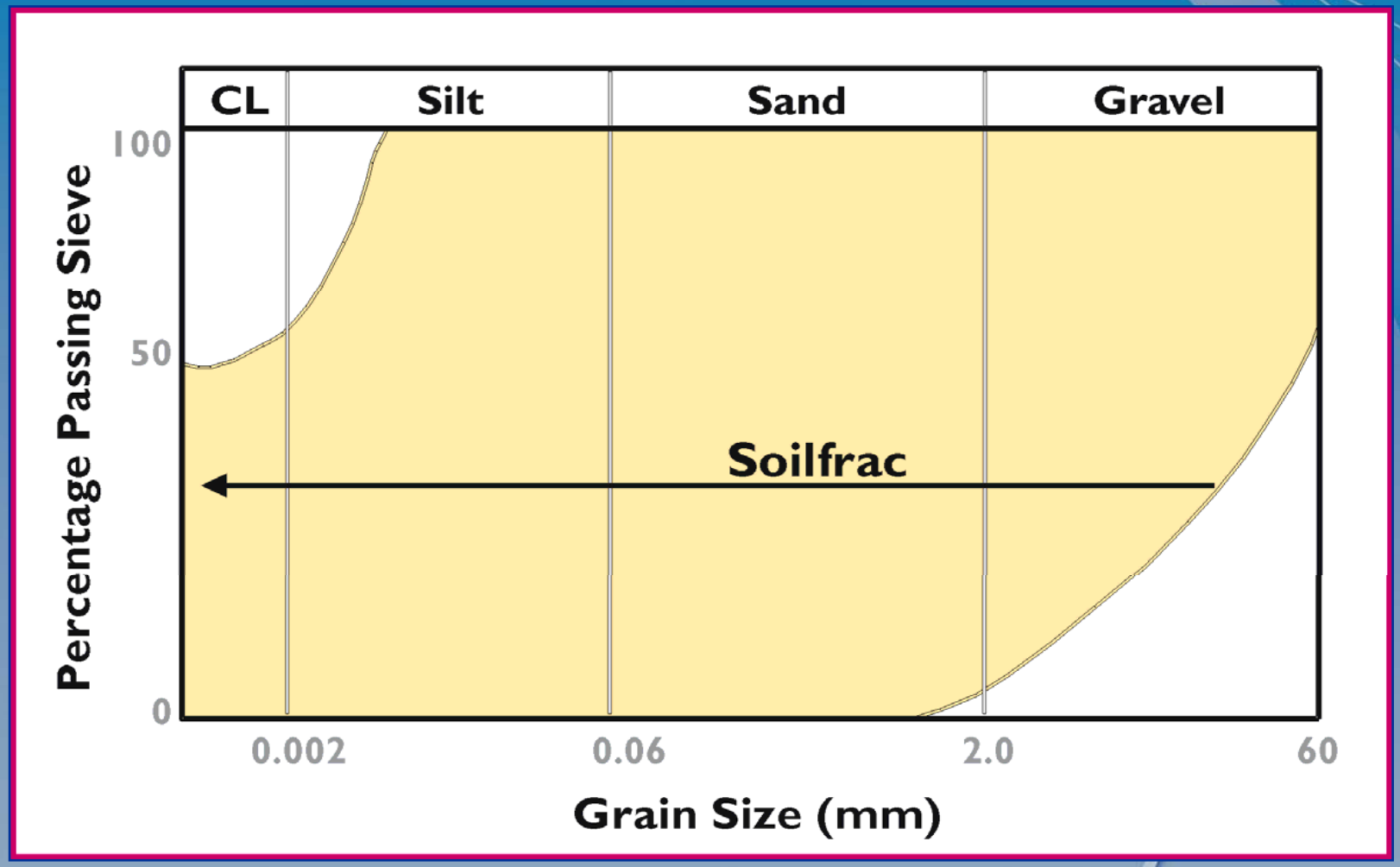
Compensation Grouting

- Pre-drilled horizontal grout holes
- Grout lenses cause expansion (heave) that counteracts settlement
- Initial grouting “preconditions” ground to point of incipient heave
- Additional lense grouting as excavation proceeds

Compensation Grouting

- Instrumentation provides real-time data feedback
  - PK nails in pavement
  - MPBXs with remote readout
  - Electrolevels
- Can control settlement during tunneling to within 3 mm

Compensation Grouting



Compensation Grout Lenses

Applications

PROJECT	DATE	DIA.	GROUTING METHOD	OVER-BURDEN	STRUCTURE
WMATA Section E-2c Washington D.C.	1994	19 ft.	Permeation (vertical Pipes)	45 ft.	Urban area
WMATA Section E-3a Washington D.C.	1995	19 ft.	Permeation (vertical Pipes)	30 ft.	Urban area
WMATA Section E-4b Washington D.C.	1994	19 ft.	Permeation (horizontal pipes and from the face)	60 ft	Historic Cemetery
WMATA Section F-6b Washington D.C.	1997	19 ft.	Permeation (vertical Pipes and from the face)	50 ft.	Public Housing Project
CNR St. Clair River Tunnel Ontario, Canada	1993	30 ft.	Compensation	30 ft.	Imperial Oil Research Building
LA Metro Hollywood Freeway Crossing Section a-130	1994	21 ft.	Permeation	19 ft.	10 – lane freeway
Arlington Cemetery Outfall	2000	48 in.	Compensation	15 ft.	Light Rail Tracks
Potomac Yards Outfall	2000	7.5 ft.	Compensation	20 ft.	Light Rail Tracks
Rio Piedras Station, San Juan PR	1998	60 ft.	Compensation	30 ft.	Urban area
MCT-1	1997	9 ft.	Compensation	70 ft.	Light Rail Tracks

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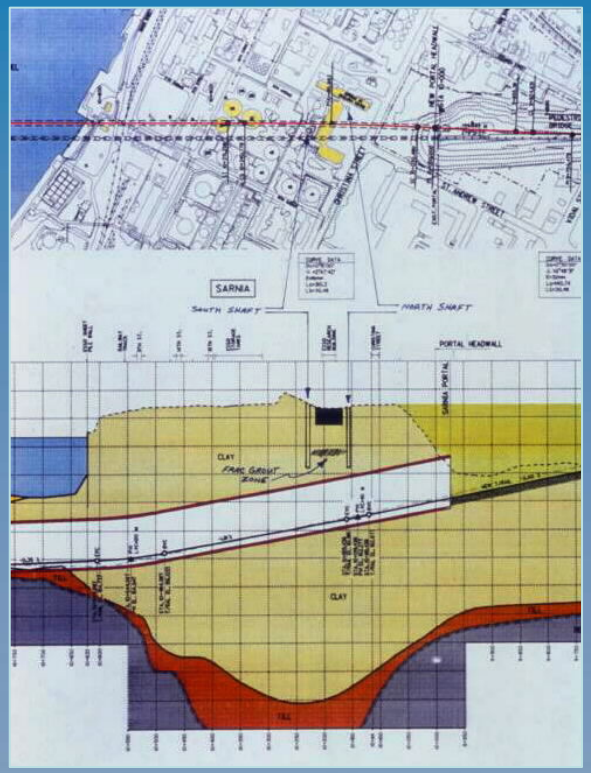
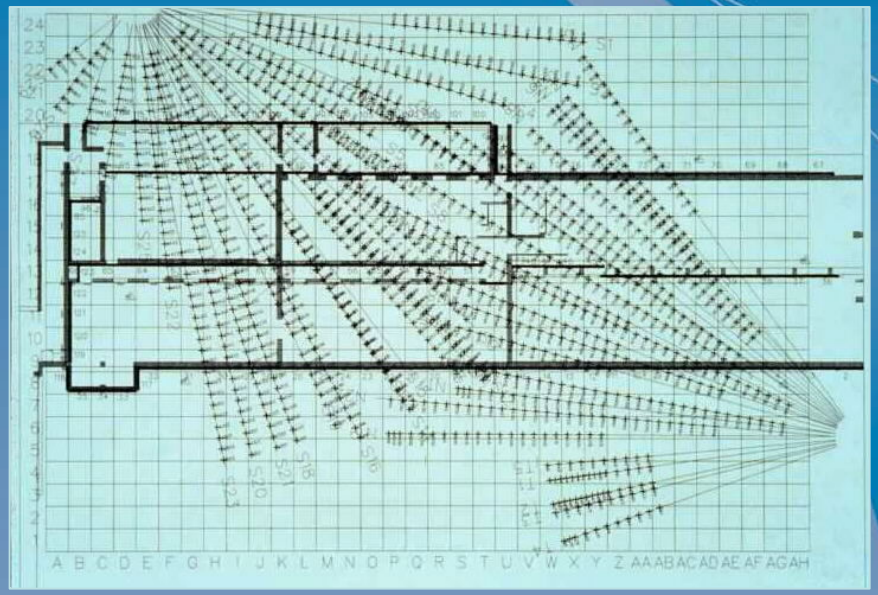
St. Clair River Tunnel

- Challenge: Protect Imperial Oil Research Facility during undercrossing by 9.2 m diameter EPB tunnel in soft clays

St. Clair River Tunnel

Tunnel Plan and Profile



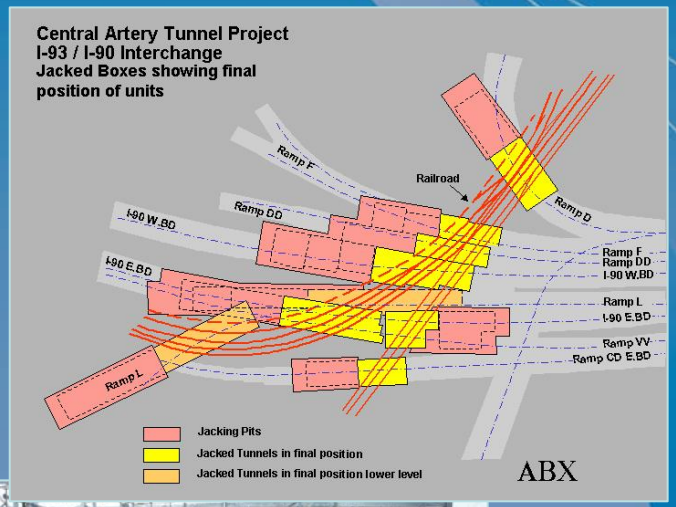


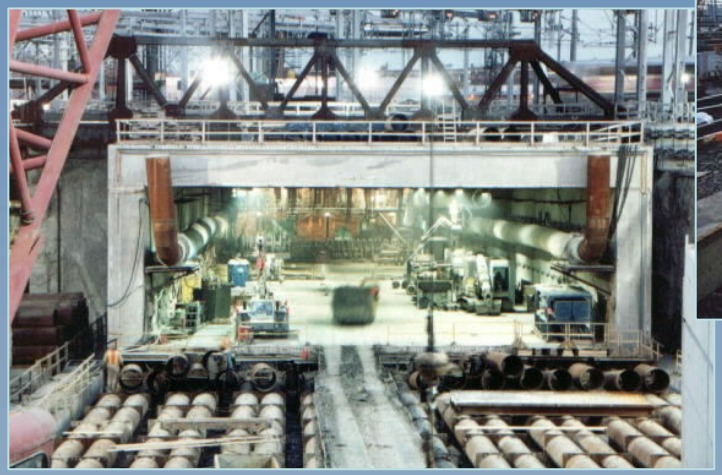
Grout Pipe Layout (2 shafts)

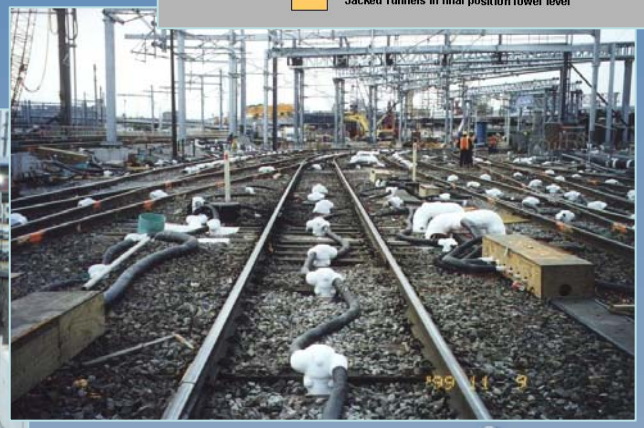
Grout Pipe Installation

Mitigation Measures

- Freezing
  - Install freeze pipes and circulate super-cooled fluid (brine or liquid nitrogen)
  - Strengthen ground prior to tunneling







Mitigation Measures

- Face Conditioning Agents
  - Polymers / additives injected into face
    - Improve ground characteristics
    - Improve passage / removal of cuttings