Long-term performance and carbon emissions associated to tunneling

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Outline

- Carbon emissions of road tunnels
- Example of vehicle operation economy – emissions and $
- Improvement of carbon emissions in tunnel construction: the role of sprayed concrete
- Long-term accidents in tunnels
- Long term monitoring of tunnel behavior
- Final remarks

Carbon emissions of road tunnels

Lifetime assessment of Norwegian road tunnels (Huang *et al*., 2013)

- 67 m^2 cross section
- Rock
- 100 years lifetime
- 1280 kWh / (m.year) for lighting, ventilation, pumps, monitoring

CO_2eq emissions due to construction

- 6.5 tons / 1m tunnel
- Energy: 9%
- Transportation of materials: 15%
- Concrete: 42%
- Diesel for construction machines: 8%
- Explosives: 4.8%
- Others …

Total emissions during lifetime (100 yr, t / m)

- Construction: 6.5
- Operation: 4.55
- Maintenance: 1.95

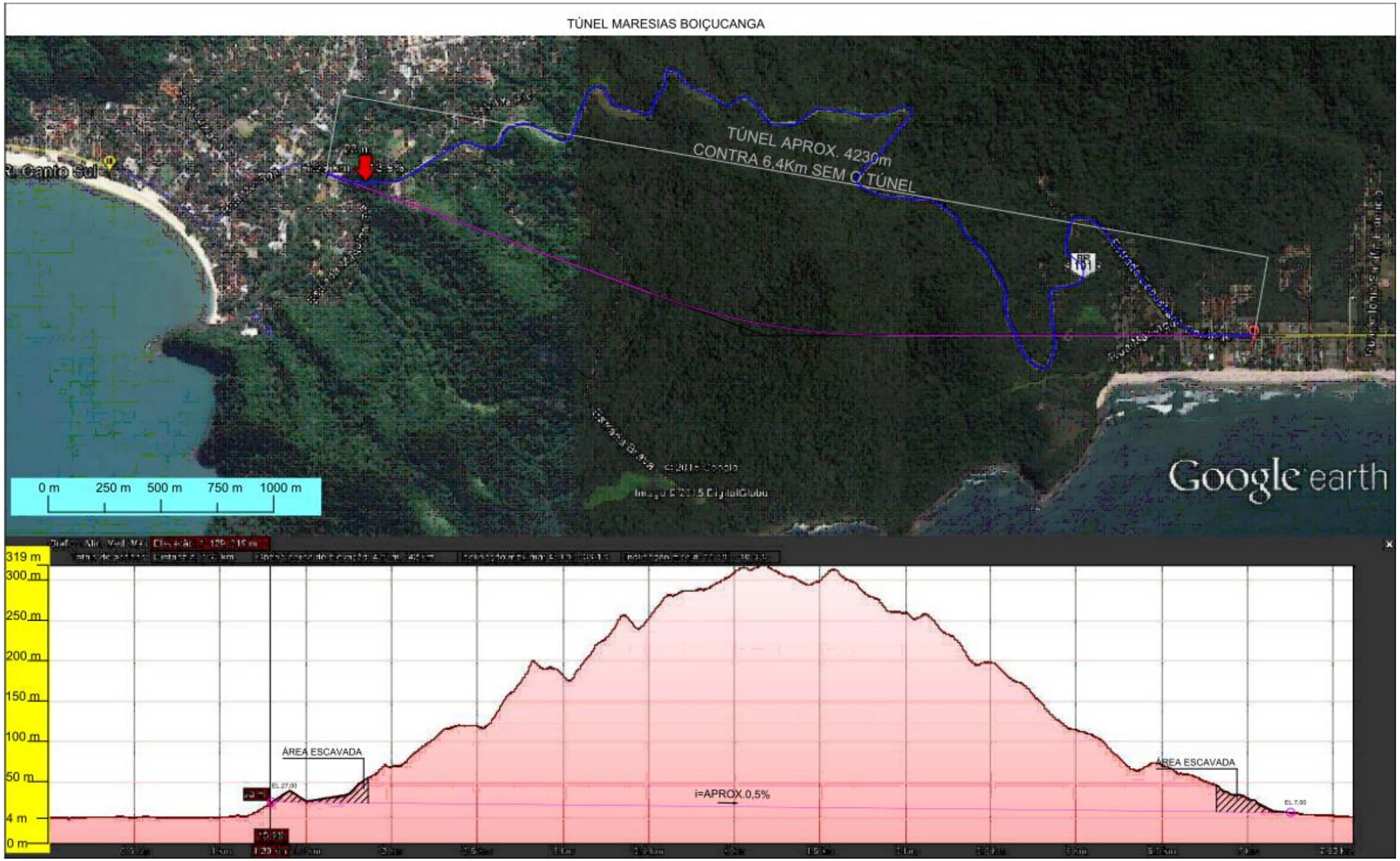
Example of vehicle operation economy – emissions and $

Example of emissions evaluation
Tunnel versus at-grade solution

- Example: SP 55 highway
- Between Maresias and Boiçucanga beaches
- Evaluation last 40 years
- Assumptions from Huang *et al.* (2013)

Cost of no-tunnel solution for roads
SP 55 Road, Northern Coast, State of São Paulo

Maresias-Boiçucanga section



SP-55 – Maresias-Boiçucanga

- Straight line distance: 4.2 km
- At-grade road: 6.4 km
- Maximum elevation: 320 m
- Gradient: 6%
- Average daily traffic: 12,325 vehic./dia

Construction, operation and maintenance CO_2eq emissions

1 – Tunnel

• Construction:	6.5*4230	27495 t
• Operation:	4.55*4230*0.4	7700 t
• Maintenance:	1.95*4230*0.4	3300 t
		38500 t

2 – At grade

- Construction:
- Operation:
- Maintenance:

Economy of vehicle emissions in 40 years if tunnel existed

• At surface:	cars	12323*65%*6420*365*40*(consumption class G)
	trucks	12323*35%*6420*365*40*(consumption class G)
• Tunnel	cars	12323*65%*4230*365*40*(consumption class A)
	trucks	12323*35%*4230*365*40*(consumption class A)

Economy with tunnel in 40 years: **470000 t CO_2eq**

Vehicle operational cost

Tunnel *vs* at-grade road

- Total additional distance traveld per year: 11.5 million km
- 288 turns around the world

- Additional vehicle operating cost:

  US$ 1,42 billion

  in the last 40 years

Additional costs of at-grade road

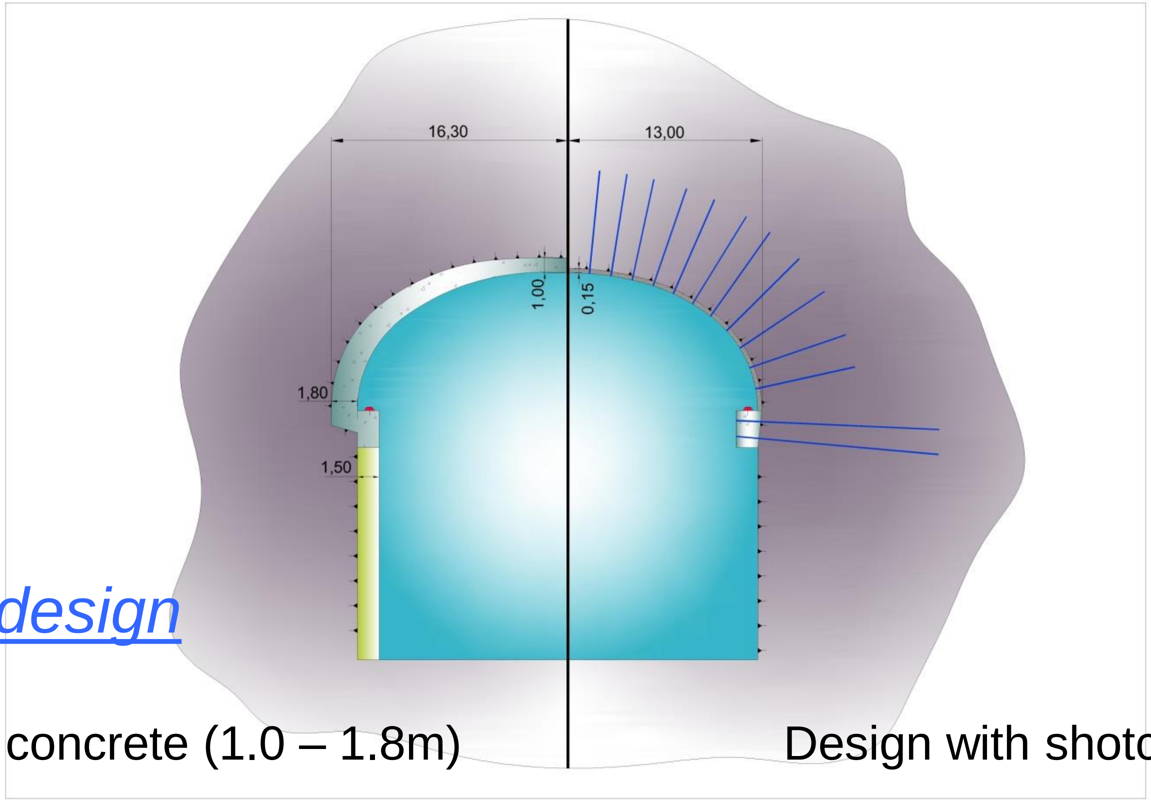
- Accidents
- Pavement maintenace
- Landslides
- Etc.


RESGATE

Sprayed concrete
Lower emissions and costs

2 TUNNELS AND SHAFTS

Paulo Afonso IV power house



92% less concrete

Abandoned design

As built

Design with cast concrete (1.0 – 1.8m)

Total excavation span: 32.6m

Design with shotcrete (0.15m)

Total excavation span: 26.0m

Single-shell lining in Germany
Single track tunnels (*Pöttler & Klapperich*, 2001)

Year	1981-83	1982	1984-87	1987-89
Ground	S/M	S/M	M	C
Pressure (bar)	0.5	0.5	0.5	0.6
Thickness (cm)	37	25	39	40

Year	1987-89	1989-90	1990-92	1991
Ground	C	M	M	G/M
Pressure (bar)	0.6	0	1.2	0
Thickness (cm)	25	40	30	35

C – claystone M – marl S - sandstone

Comments by *Pöttler & Klapperich*, 2001

- 10 - 15% savings due to single shell concept
- Scattered considerations about load on the second layer:

  full load to partial load
- Different design philosophy → even more significant savings

Single-shell lining in São Paulo

Single track tunnels

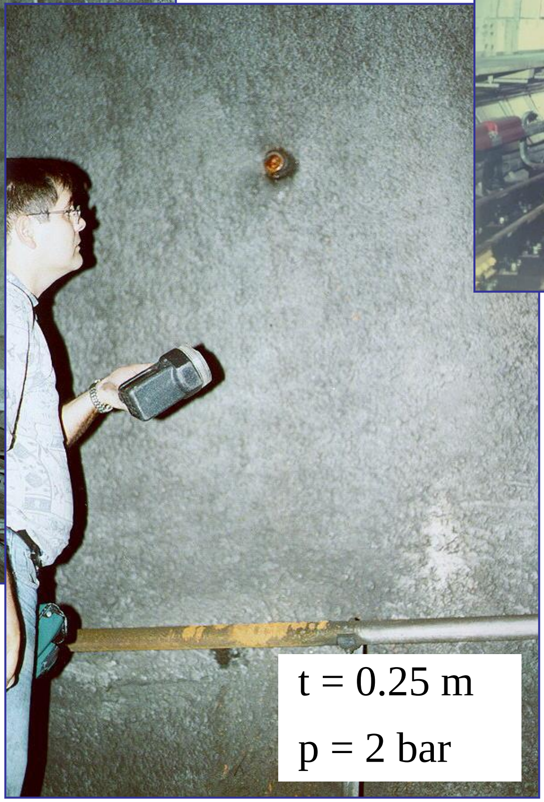
- Year: since 1981
- Ground: stiff clay with water-bearing sand layers
- Pressure: 0.5 to 2.0 bar
- Total thickness: 20 to 25 cm

2 TUNNELS AND SHAFTS

Shotcrete lining for the São Paulo Subway

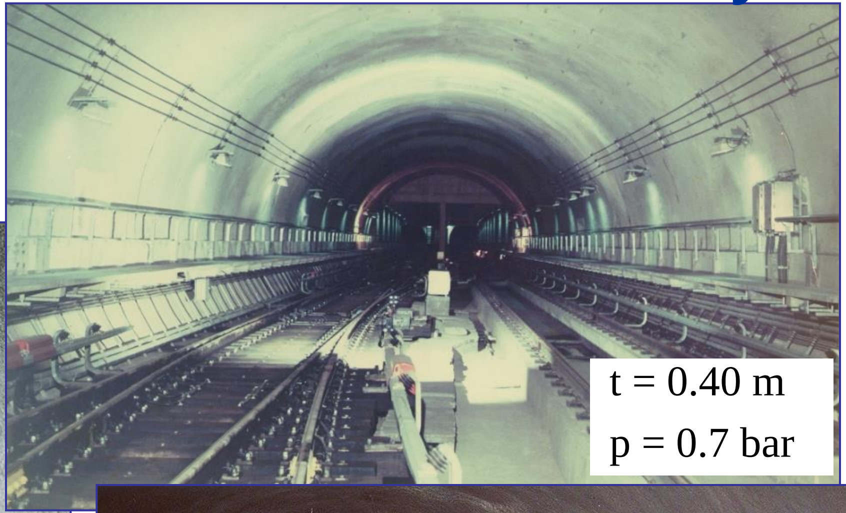
t = 0.25 m

p = 2 bar



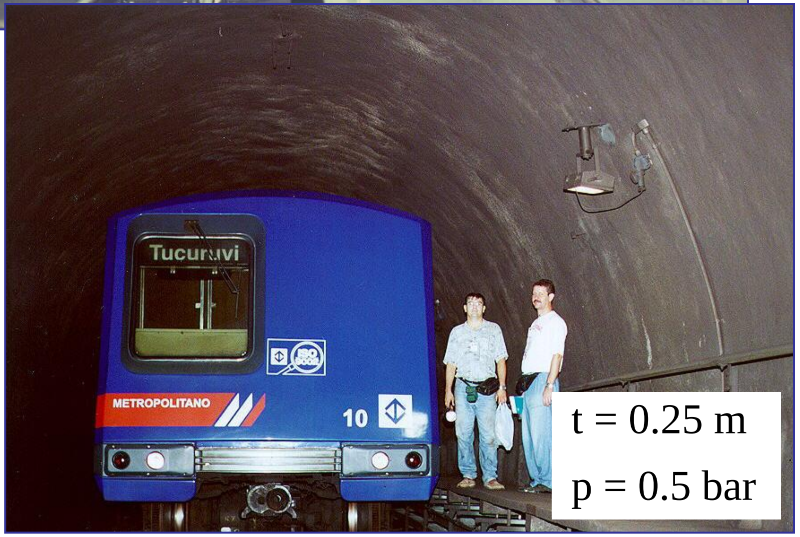
t = 0.25 m

p = 2 bar



t = 0.40 m

p = 0.7 bar



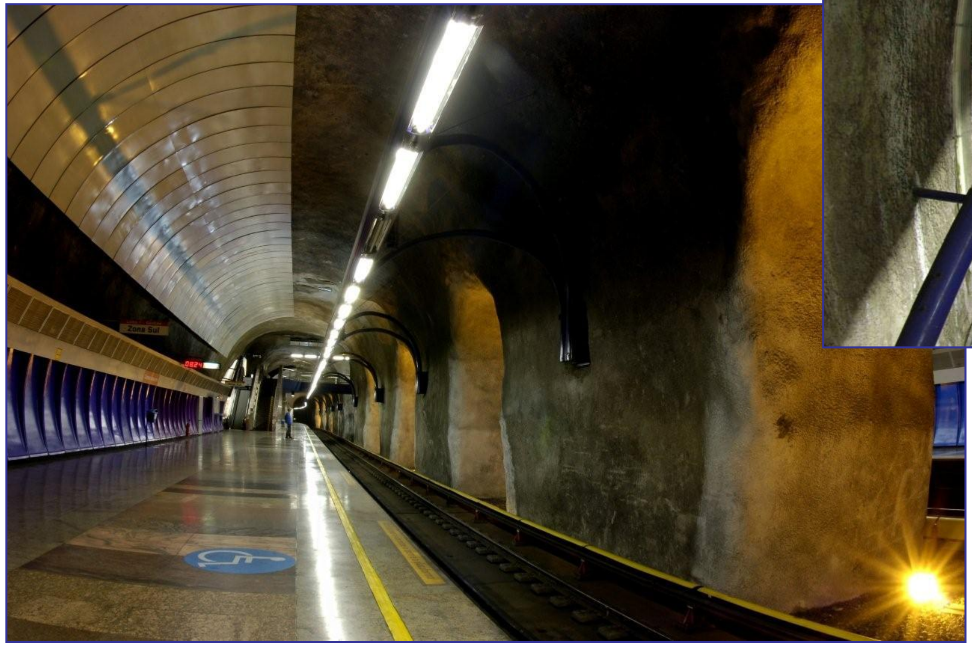
t = 0.25 m

p = 0.5 bar

São Paulo Ring Road
200 m2
4 lanes 86,000 vehic/day

2 TUNNELS AND SHAFTS

Rio de Janeiro Metro - Arcoverde Station

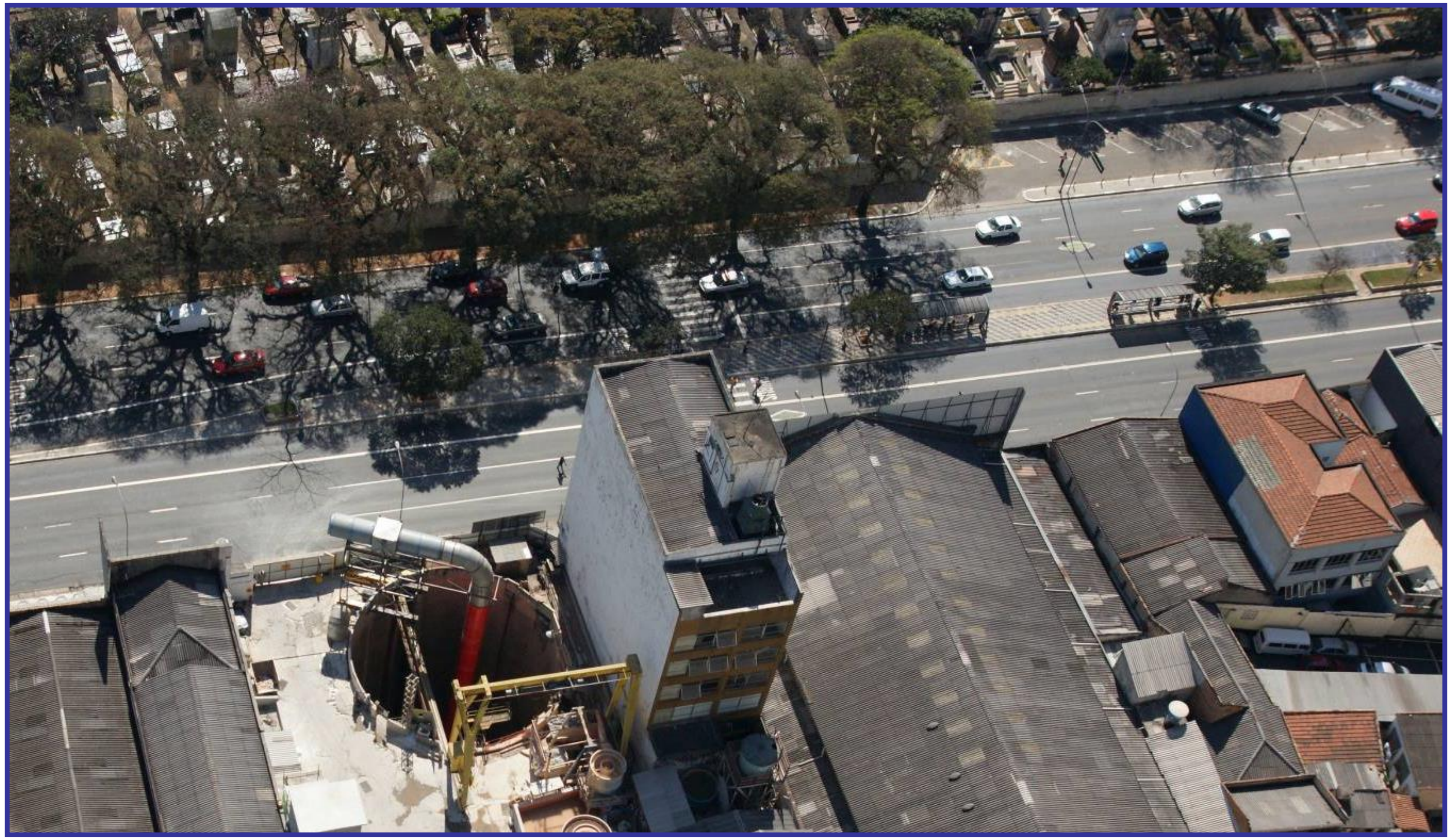


2 TUNNELS AND SHAFTS

Stockholm Metro

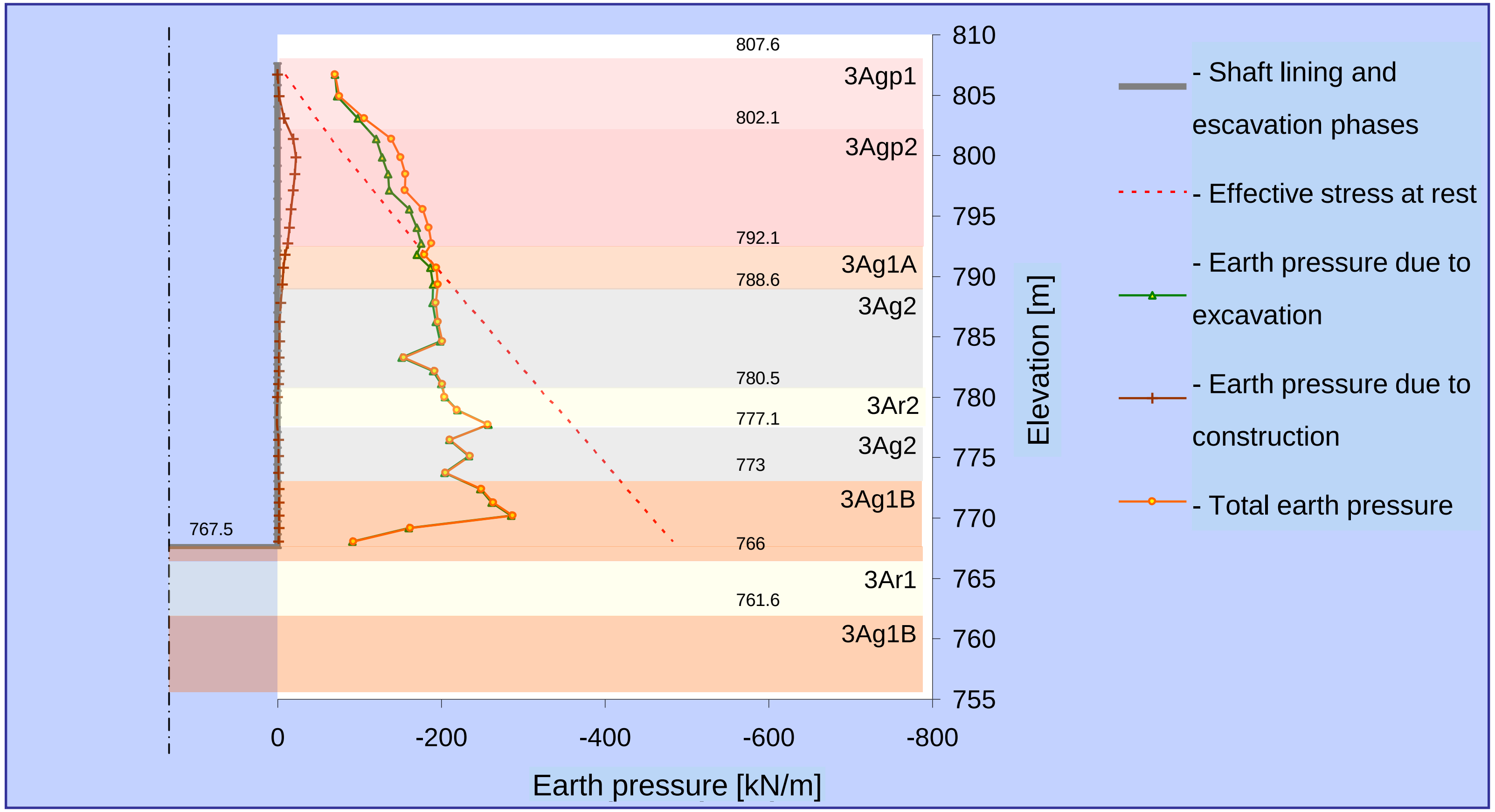
2 TUNNELS AND SHAFTS

Shotcrete Supported Shafts
José Eusébio Shaft, São Paulo Line 4



2 TUNNELS AND SHAFTS

José Eusébio Shaft

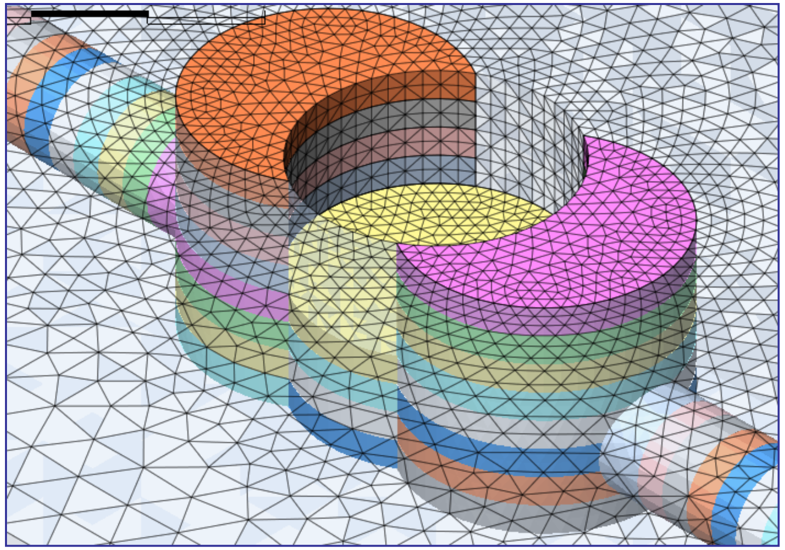


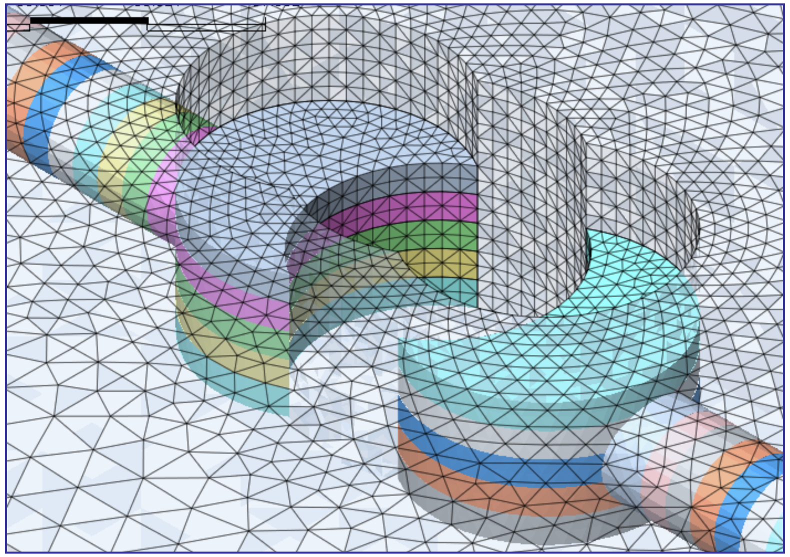
2 TUNNELS AND SHAFTS

São Paulo Metro Luz Station Shaft

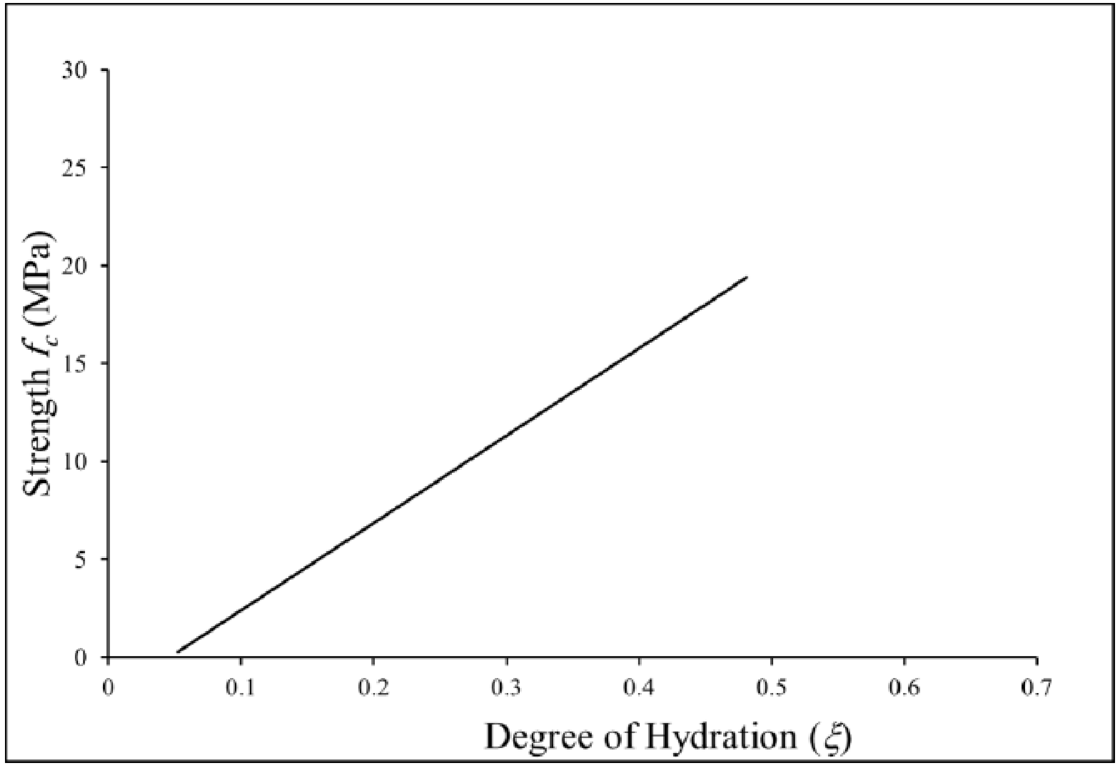
2 TUNNELS AND SHAFTS

3D simulation

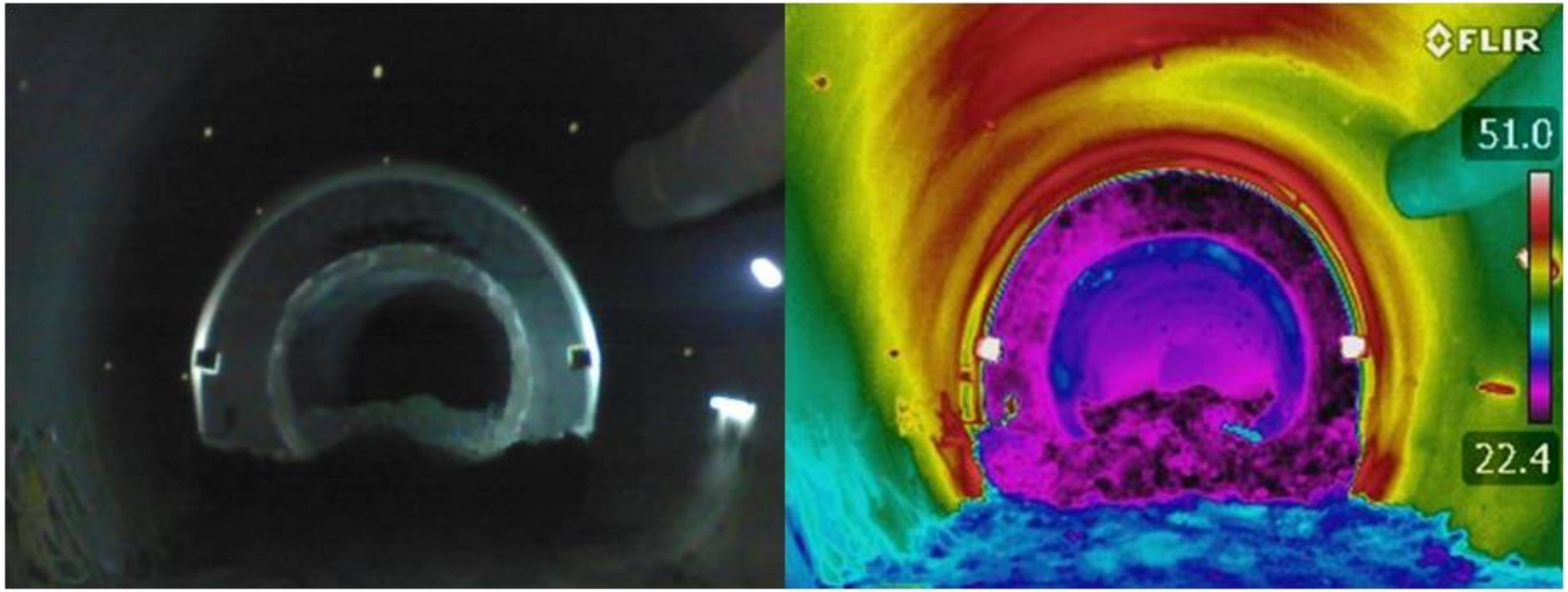




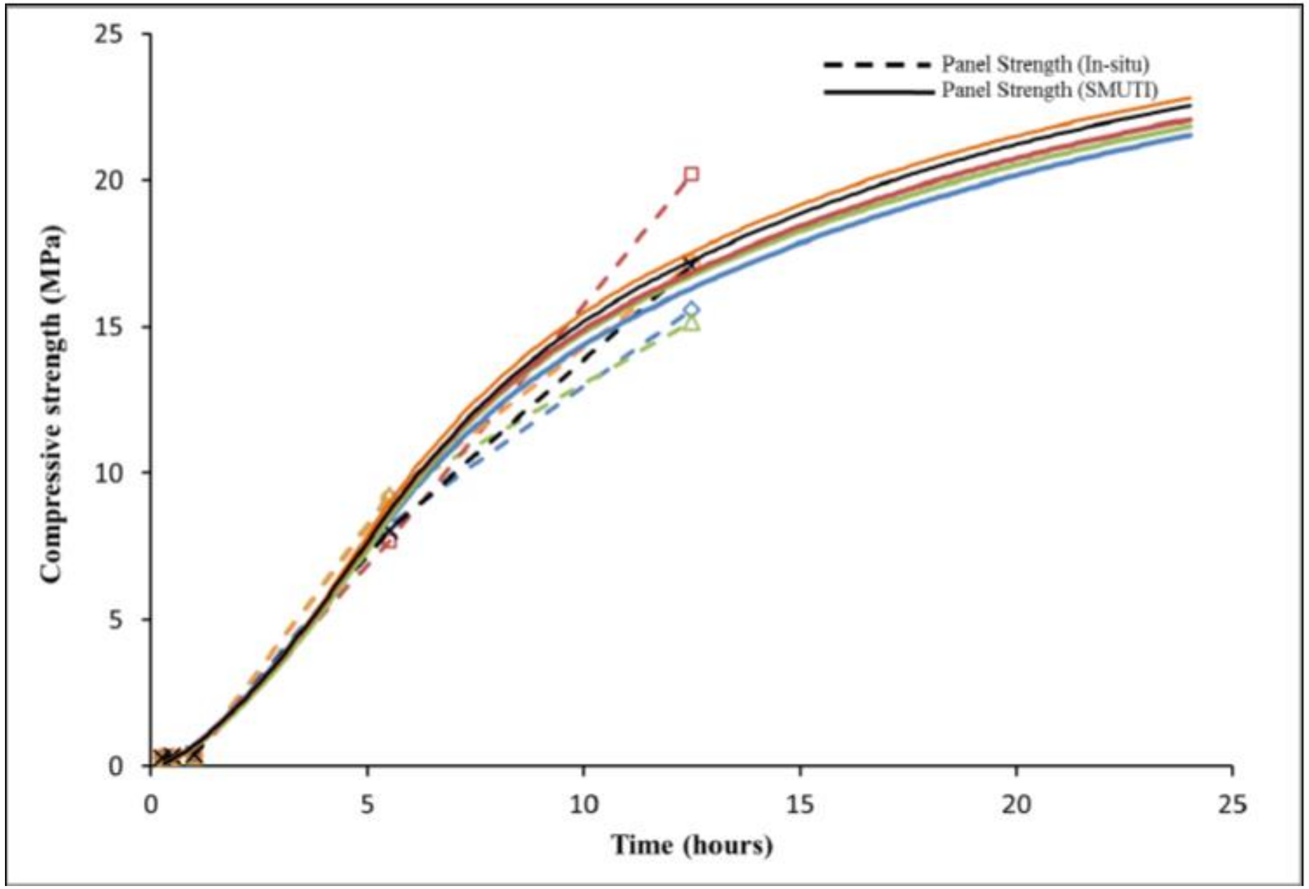
SMUTI™ – evolution of strength with degree of hydration



Thermal scanning



Measured and evaluated compressive strengths



Long-term accidents in tunnels

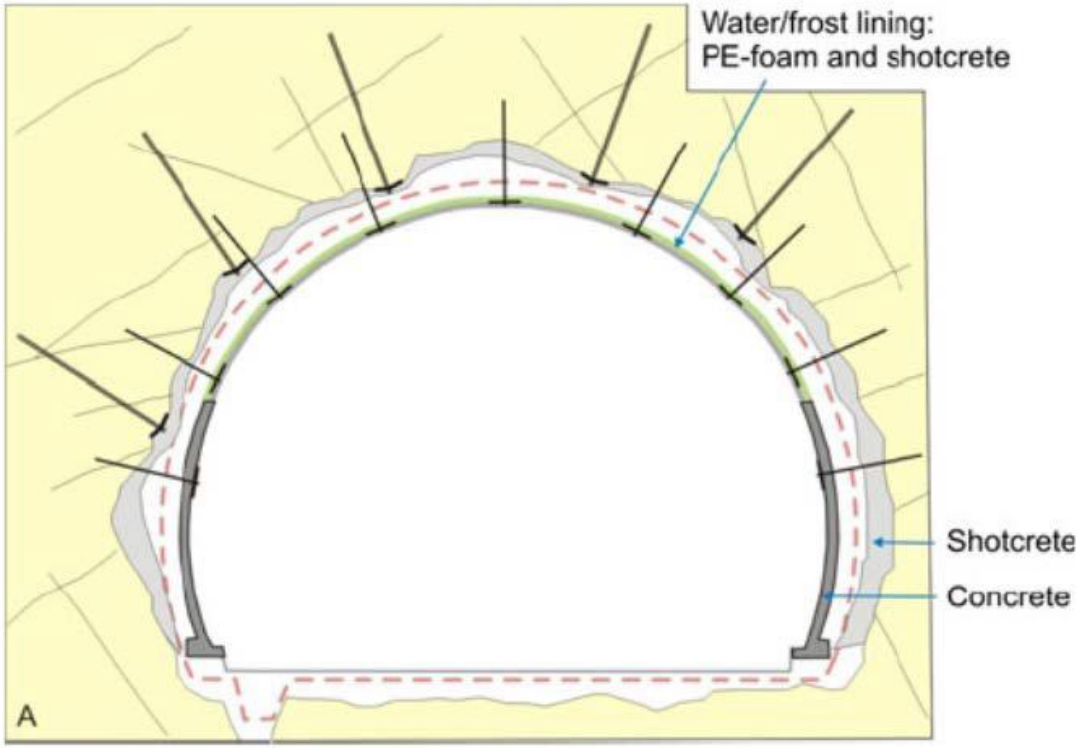
Two examples

Guandu Tunnel

- Water supply to Rio de Janeiro
- Constructed in the early 1960s
- Decrease of water flow
- Inspection: major collapse in fault zone
- Swelling clay

- Similar problems in tunnels of the Cantareira water supply system, São Paulo
- Contributions by Selmer-Olsen

Hanekleiv road tunnel, Norway
Christmas 2006



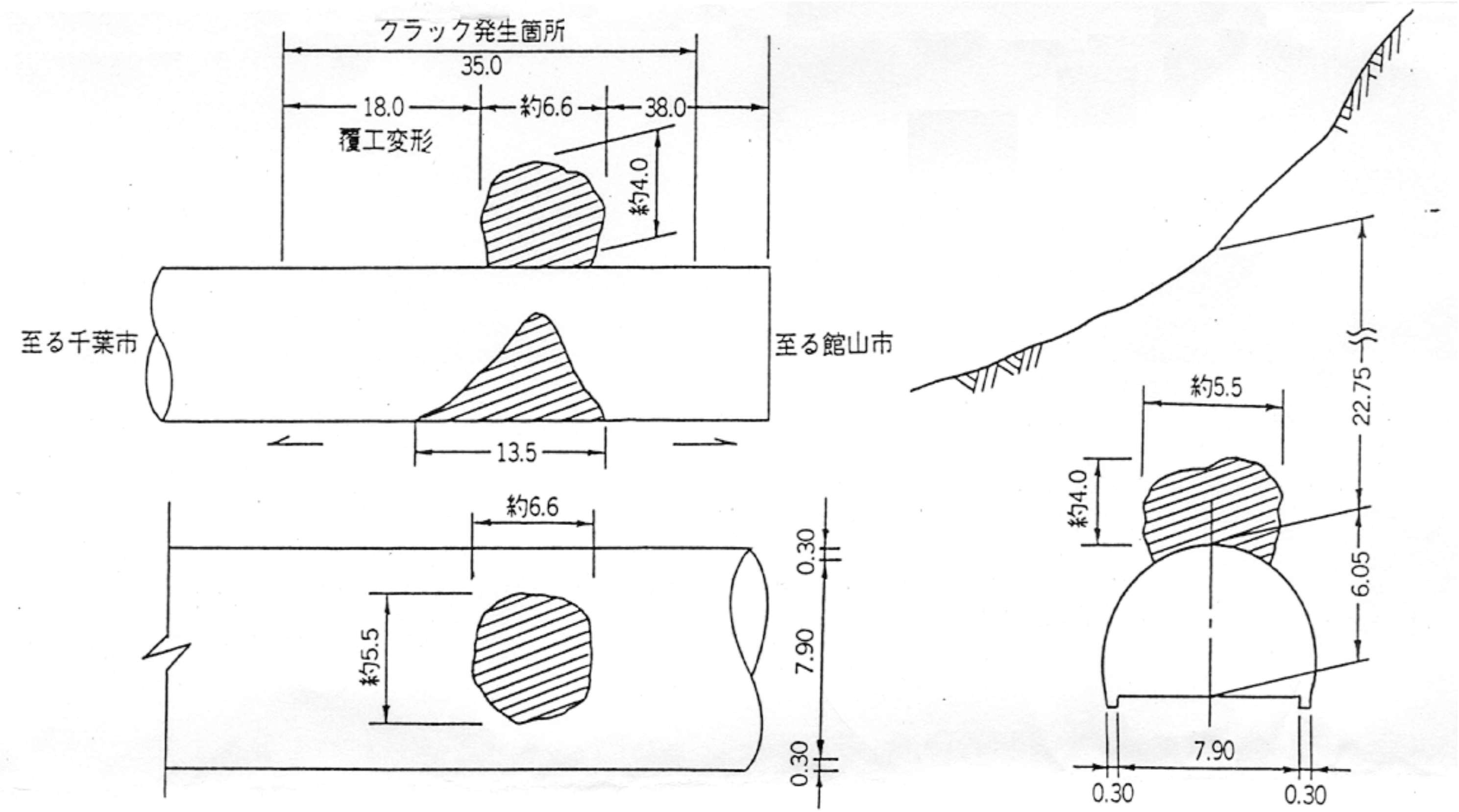
Hanekleiv Tunnel
Mao *et al.* (2015)

- Collapse 10 years after completion
- Fault zone in syenite
- Q = 0.01 – 0.02 (extremely poor)
- Fault gouge 5-10 cm thick, low content of swelling clay

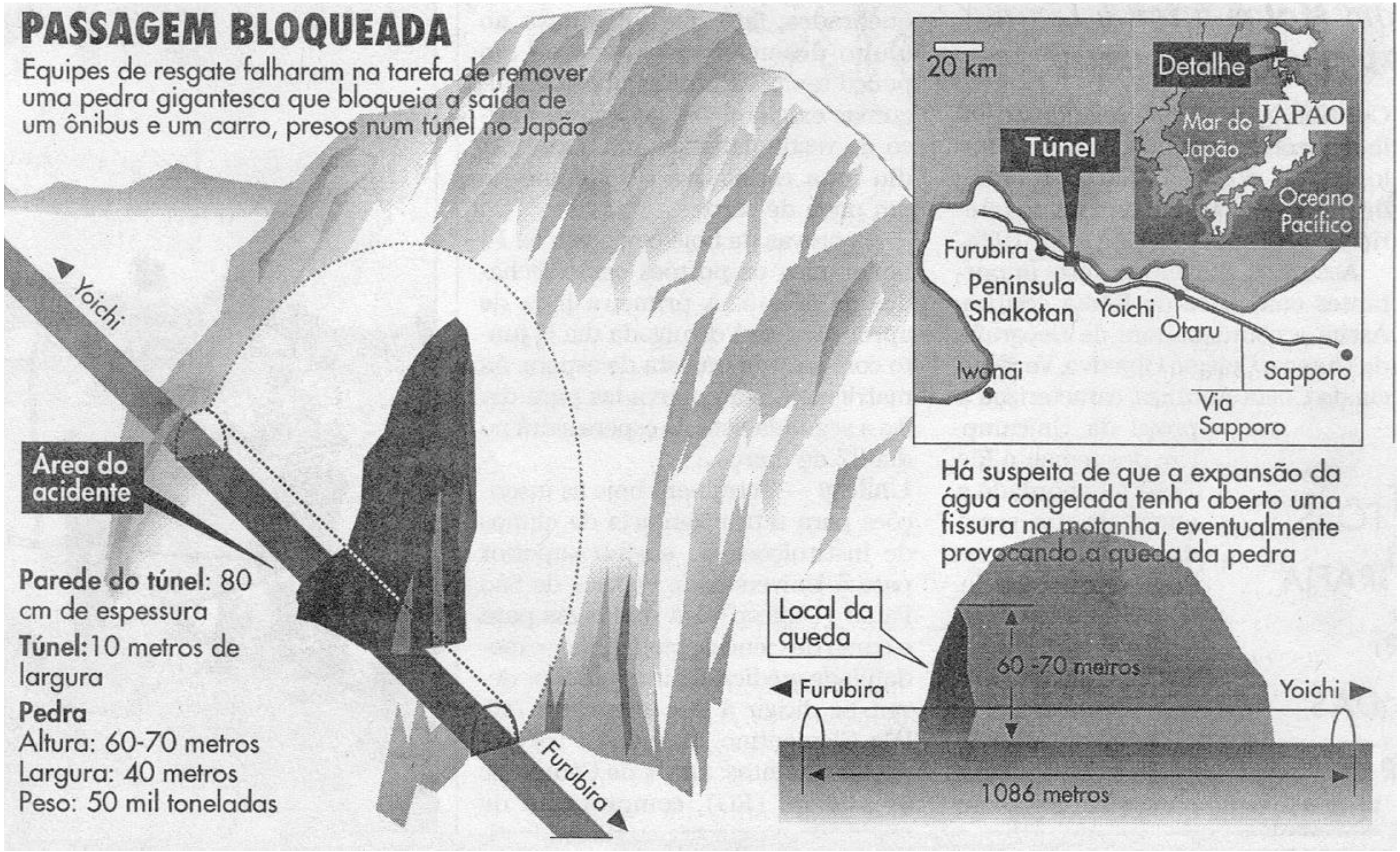
Hanekleiv Tunnel
Mao *et al.* (2015)

- 15 cm of steel fiber reinforced spayed concrete
- Cracks during construction
- Additional 10 cm sprayed concrete before cladding
- Collapse: 250 m3
- One large block (several tons); mainly small blocks, gravel and fragments of altered syenite
- Conclusion: insufficient support

Collapse Koyamano Road Tunnel, Japan
Inokuma (1990)



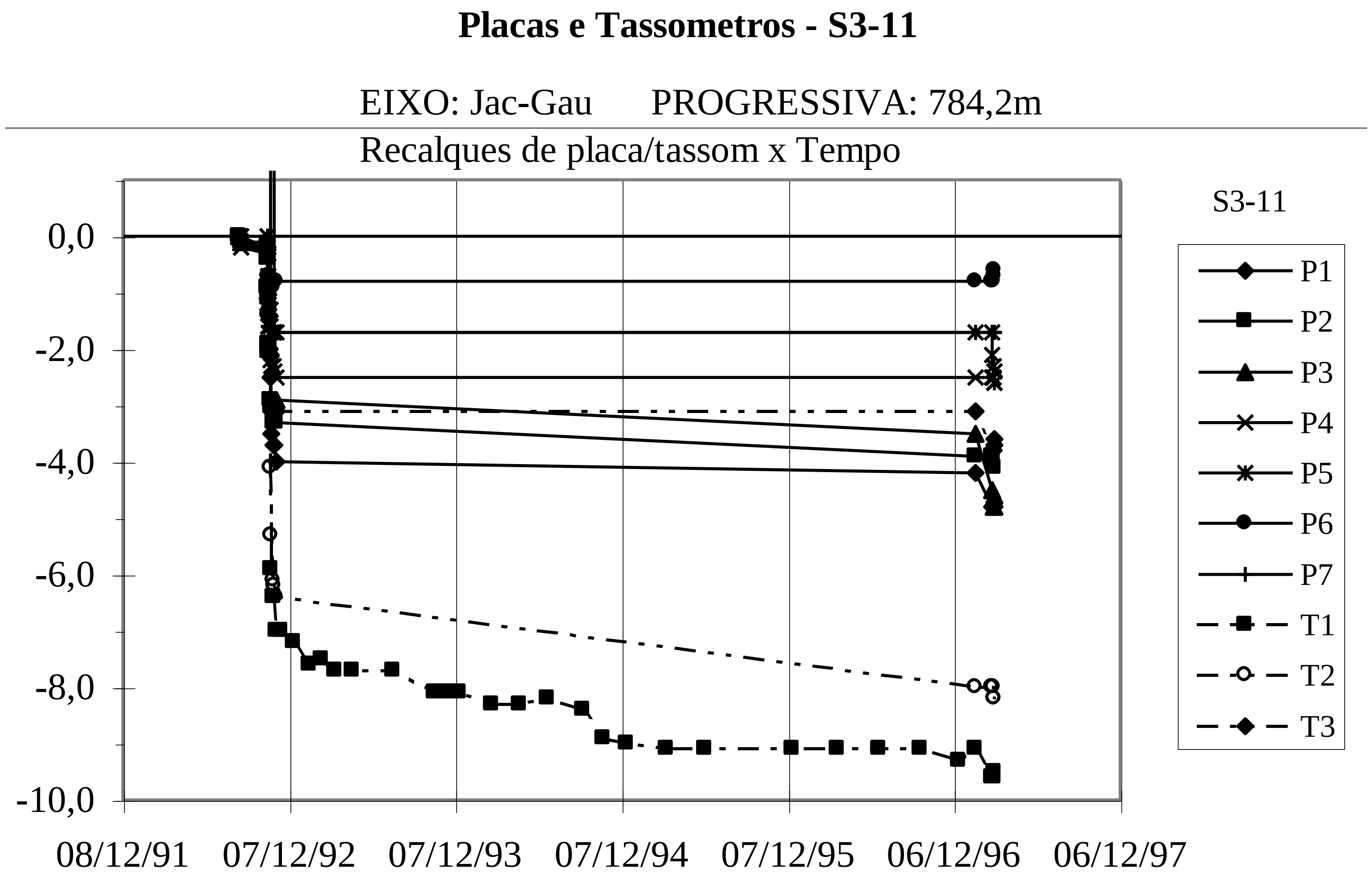
Construção: Março 1967 (Conclusão)
Acidente : 04/02/1990


PASSAGEM BLOQUEADA
Equipes de resgate falharam na tarefa de remover uma pedra gigantesca que bloqueia a saída de um ônibus e um carro, presos num túnel no Japão
Yoichi
Área do acidente
Parede do túnel: 80 cm de espessura
Túnel: 10 metros de largura
Pedra
Altura: 60-70 metros
Largura: 40 metros
Peso: 50 mil toneladas
Furubira
20 km
Detalhe
Mar do Japão
JAPÃO
Oceano Pacífico
Túnel
Furubira
Península Shakotan
Yoichi
Otaru
Iwanai
Sapporo
Via Sapporo
Há suspeita de que a expansão da água congelada tenha aberto uma fissura na motanha, eventualmente provocando a queda da pedra
Local da queda
60 -70 metros
Furubira
Yoichi
1086 metros

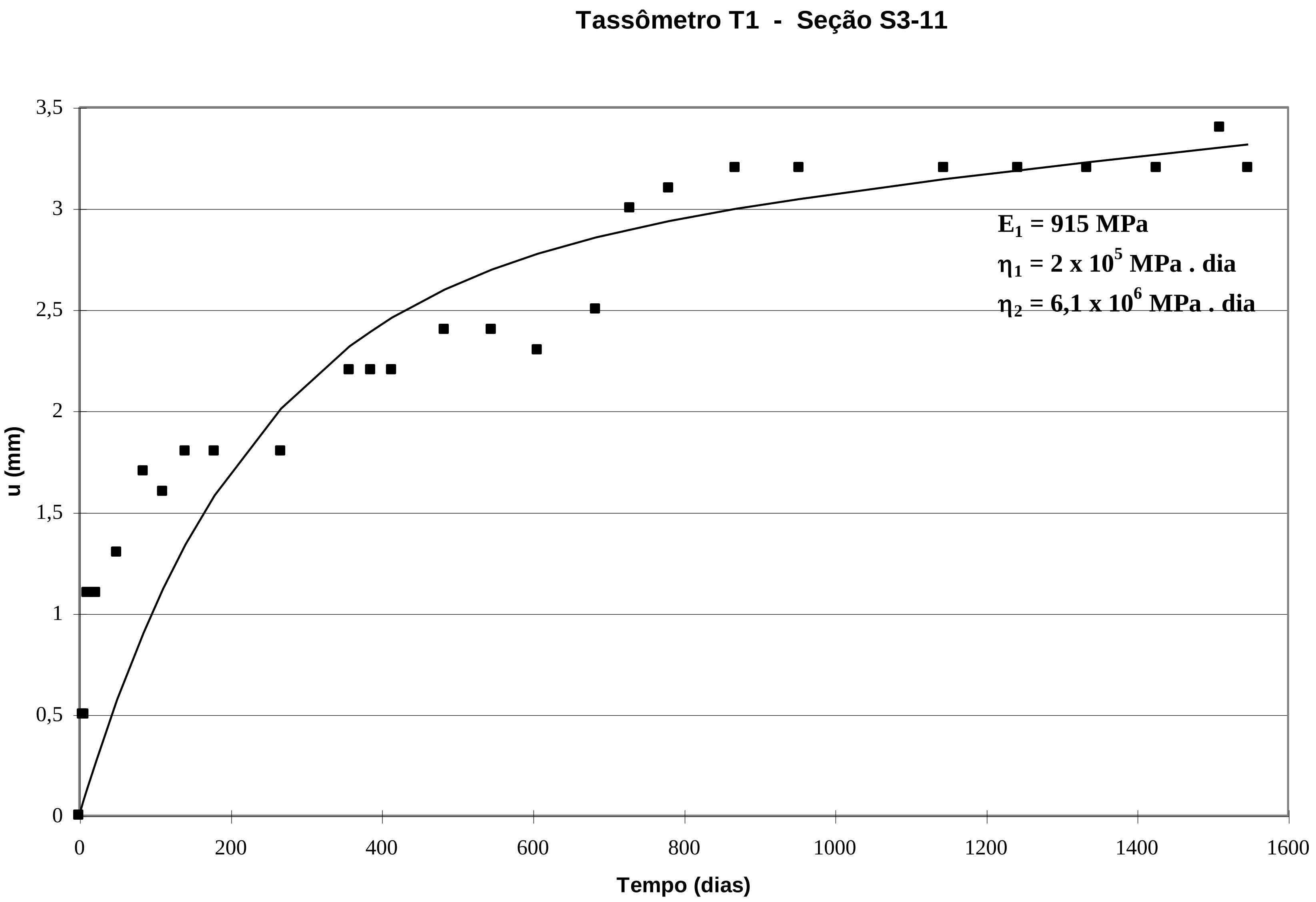
Tunnel dimensions:	B = 8,50m H = 6,05m
Overburden:	20m
Lining:	30cm Concrete
Daily traffic:	15.700 Vehic/Day
Ground mass:	Sandy silt
Warning:	Cracks and water one day before
Probable cause:	Seepage, carrying solids
Voids:	Load increase

Long term monitoring of tunnels

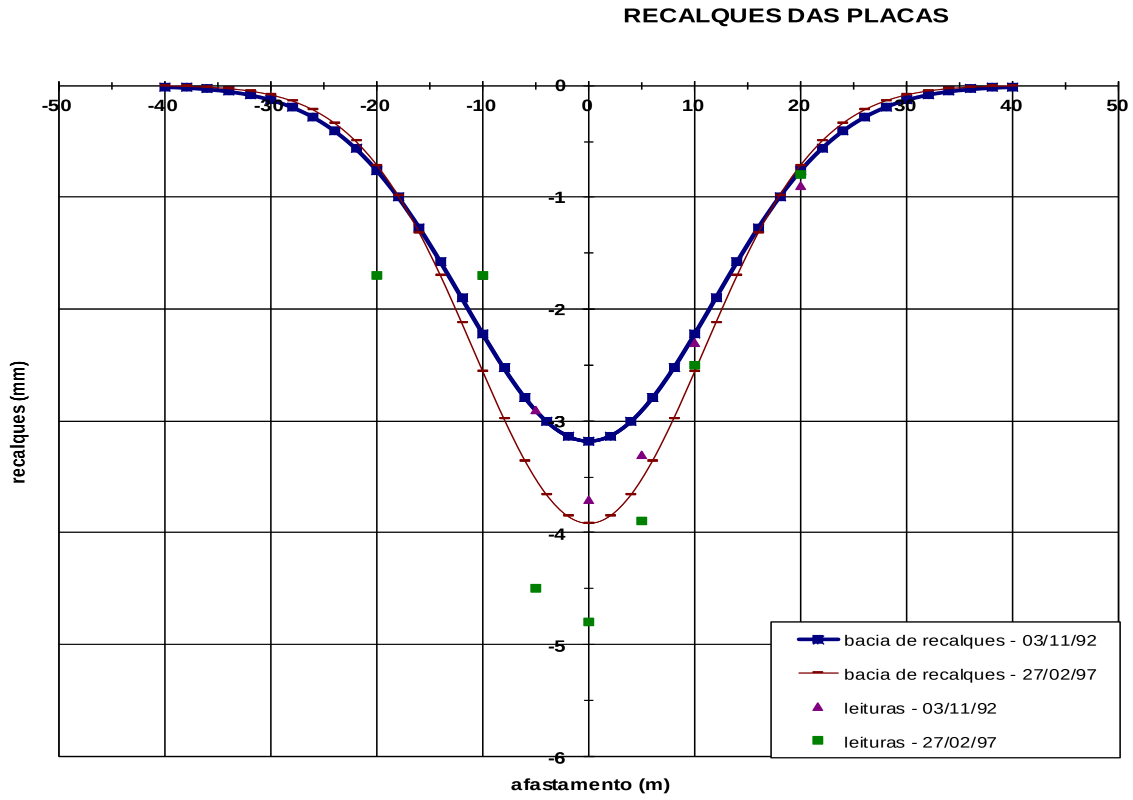
Examples of tunnels in Tertiary stiff clays and sands



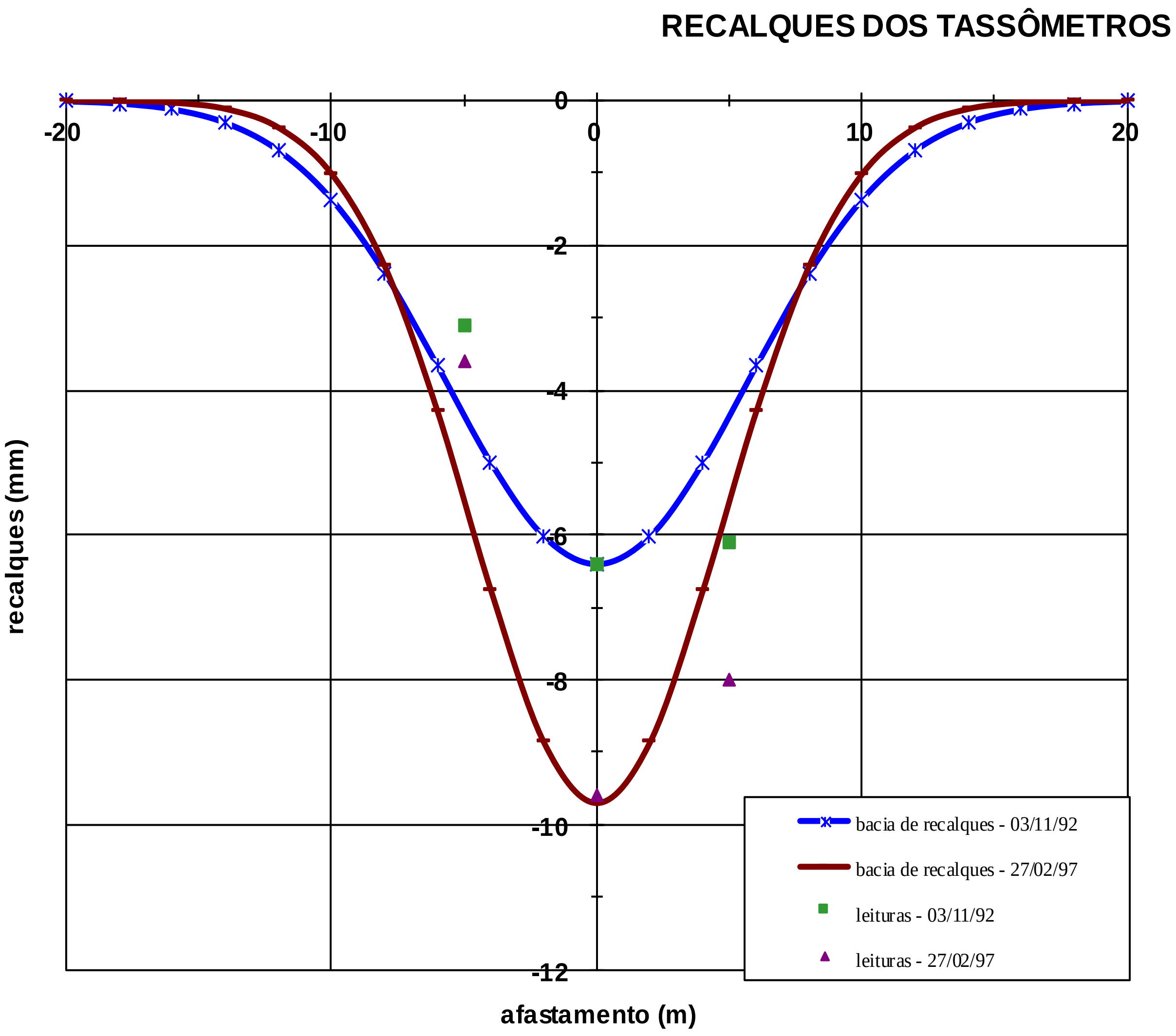
Settlements along 4.5 years
Jaciporã Tunnel, Line 2, São Paulo Metro



Curve fitting Burger’s viscoelastic model



Evolution of surface settlement trough



Evolution of deep settlement trough

Final remarks

- Emissions during tunnel construction and operations are not large.
- Concrete represents a large amount
- Sprayed concrete lining largely reduces emissions (and cost)
- Emissions and vehicle operational cost due to tunnels is remarkable
- Long-term accidents are rare; need for low-cost and feasible monitoring

Thank you!