



Tópicos Especiais em Solos e Rochas

Obras Subterrâneas

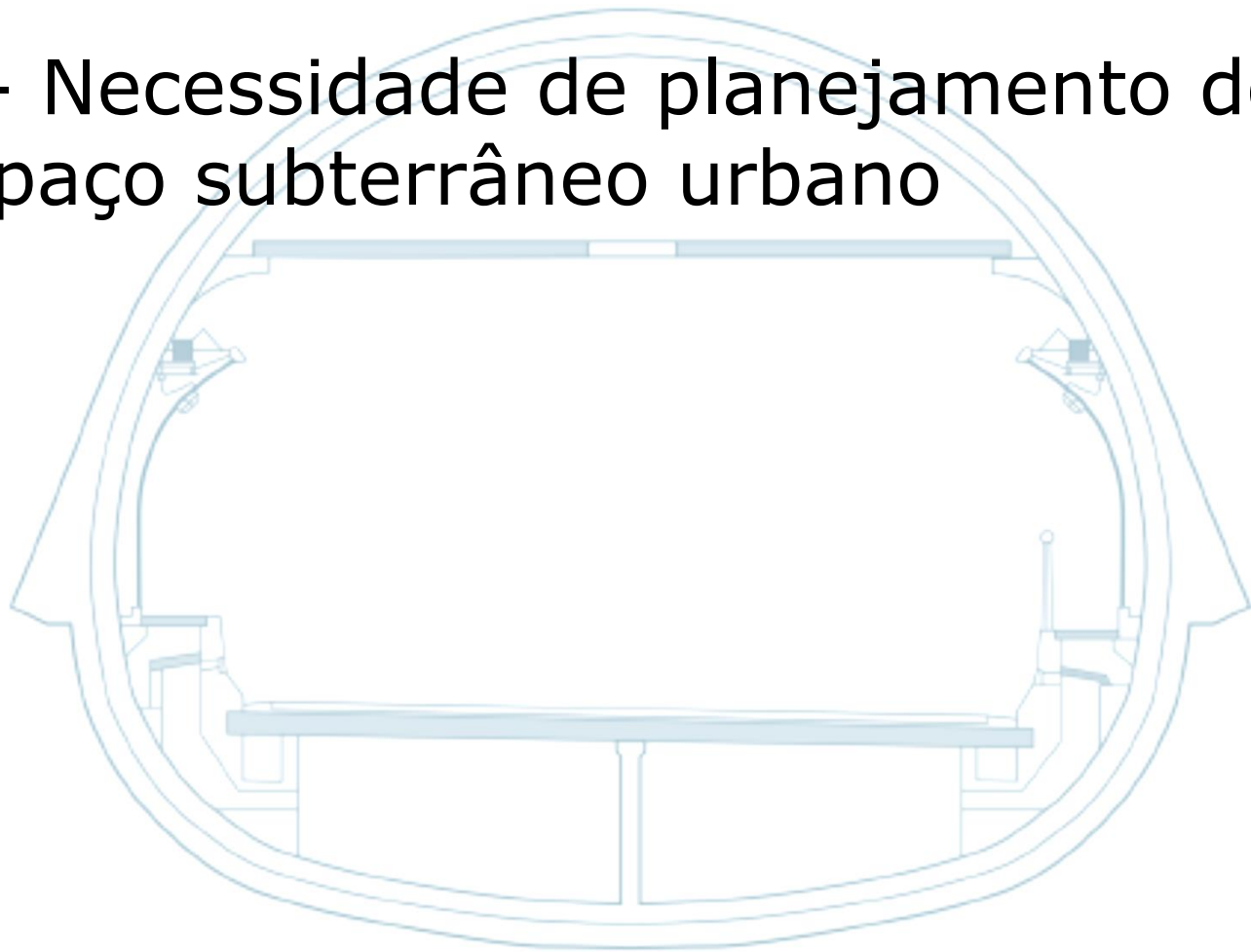
Tarcísio B. Celestino
Depto. de Geotecnia, EESC-USP
Themag Engenharia

6/5/2015

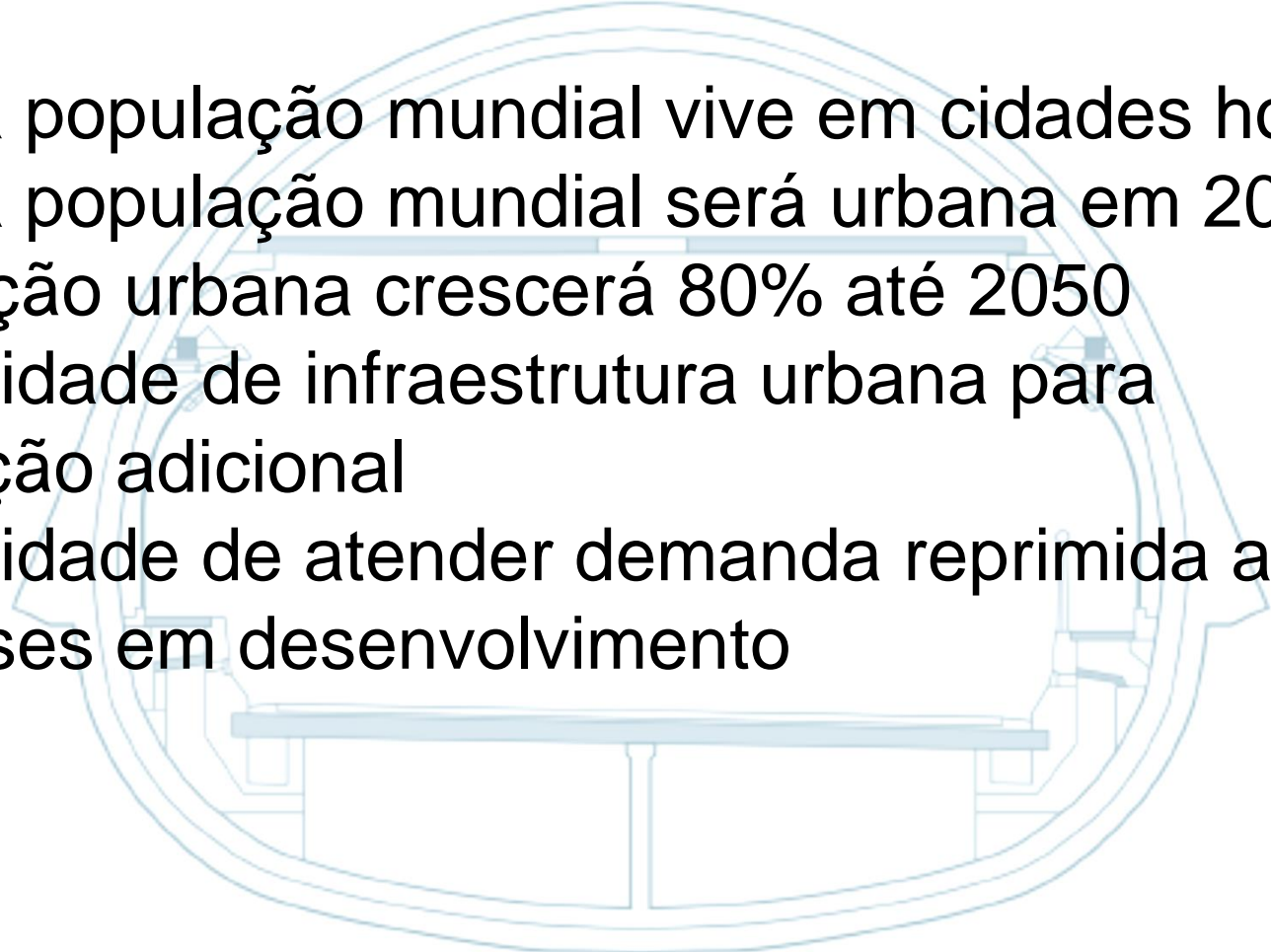
Conteúdo

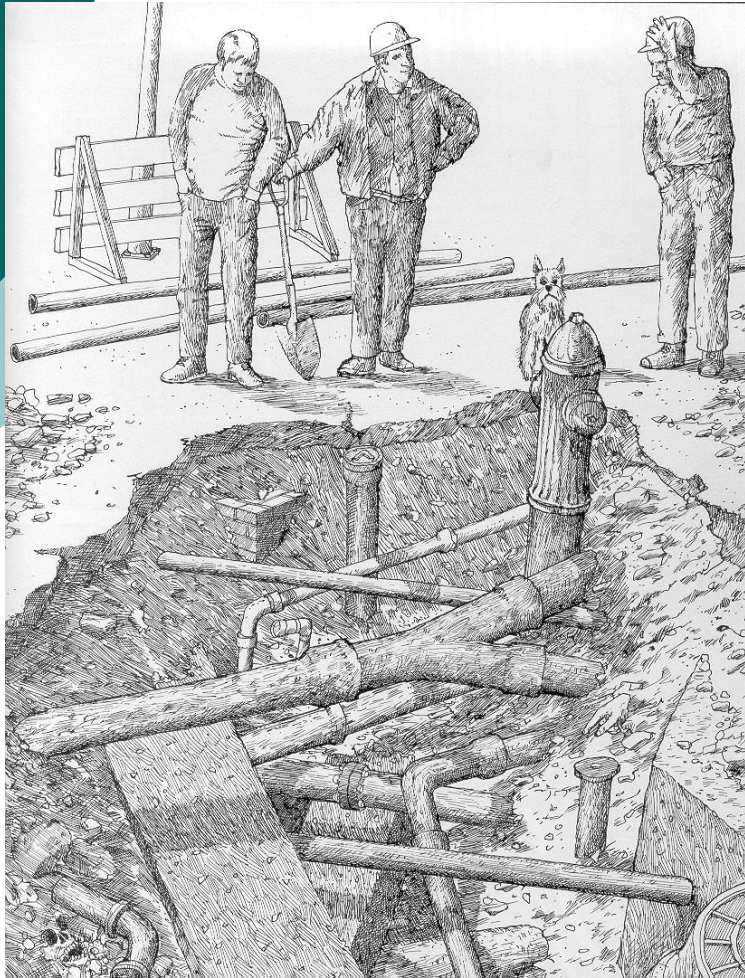
1. Necessidade de planejamento do espaço subterrâneo urbano
2. Enganos e evolução de conceitos na ligação São Paulo – Santos
3. Confiabilidade e segurança de túneis
4. Algumas obras subterrâneas em São Paulo
5. Conceitos de projetos de túneis
6. Túnel Imerso Santos-Guarujá

1 - Necessidade de planejamento do espaço subterrâneo urbano



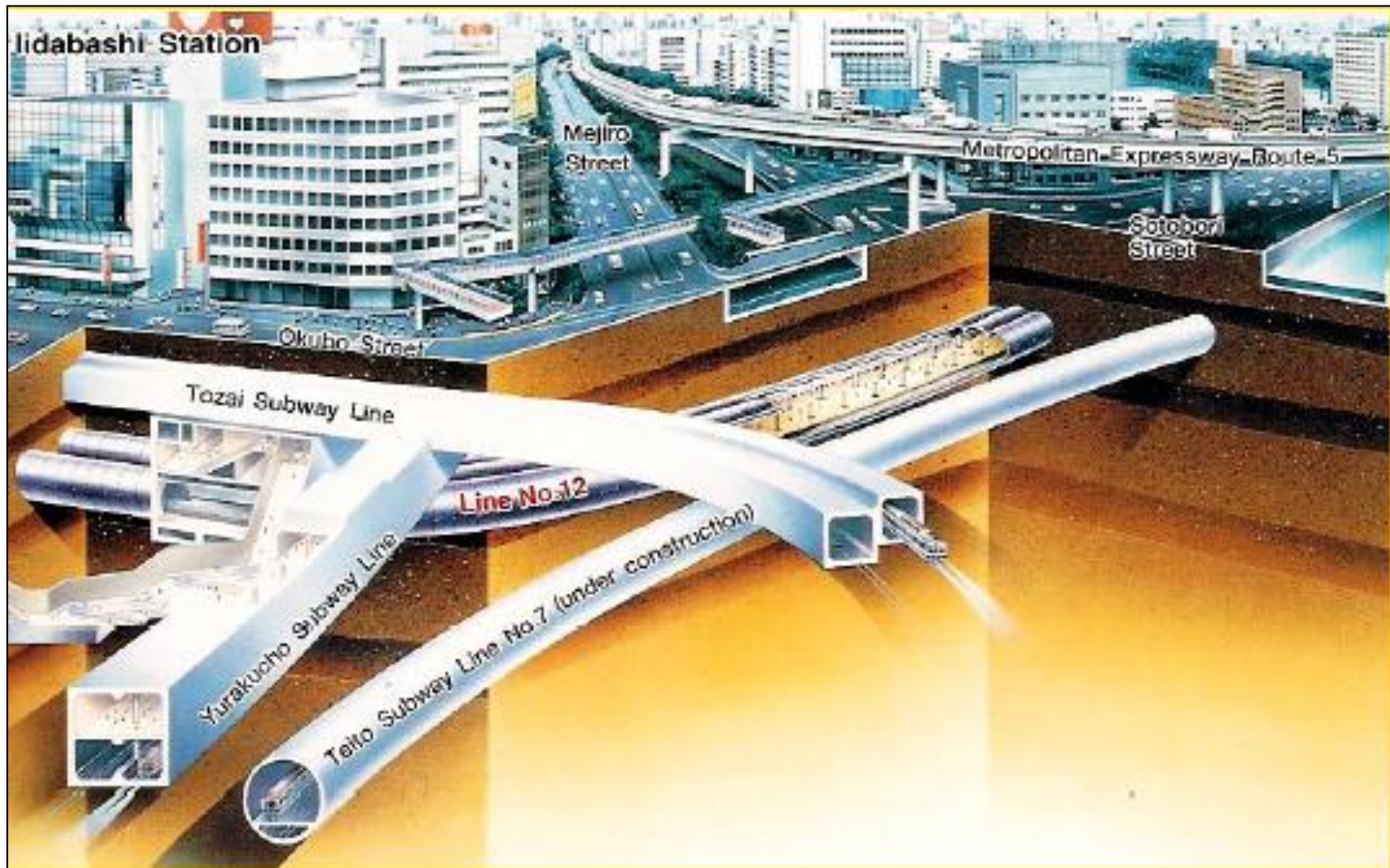
Necessidade de planejamento do espaço subterrâneo urbano

- 50% da população mundial vive em cidades hoje
 - 70% da população mundial será urbana em 2050
 - População urbana crescerá 80% até 2050
 - Necessidade de infraestrutura urbana para população adicional
 - Necessidade de atender demanda reprimida atual em países em desenvolvimento
- 



- “Underground chaos” (Cornaro & Admiraal, 2012)
- “É de quem chegar primeiro”
- Consequências proporcionais à escala da obra: custo e prazo

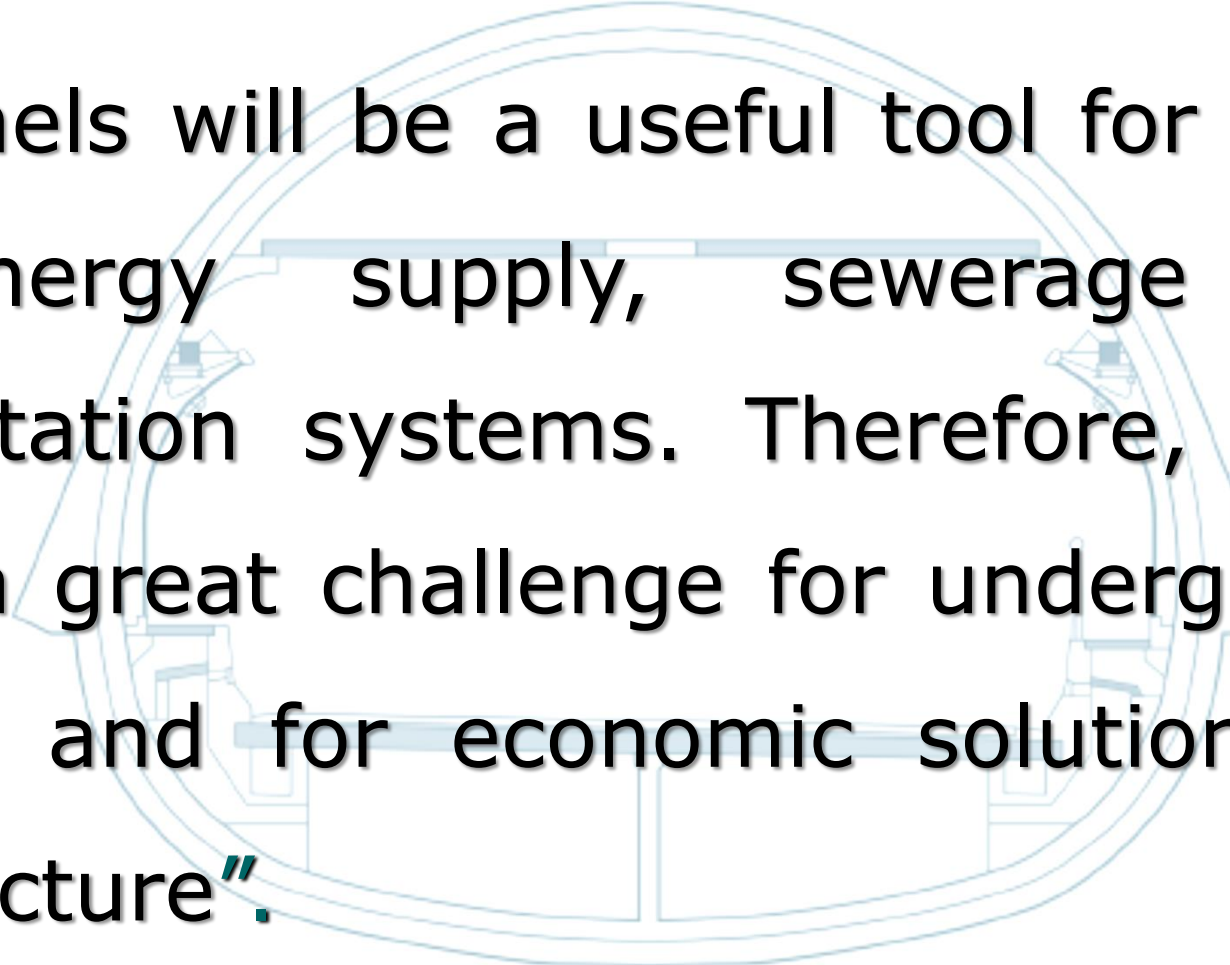
Racionalização de uso do solo



Estação Iidabashi
Tóquio – Japão

Importância de túneis para infraestrutura urbana

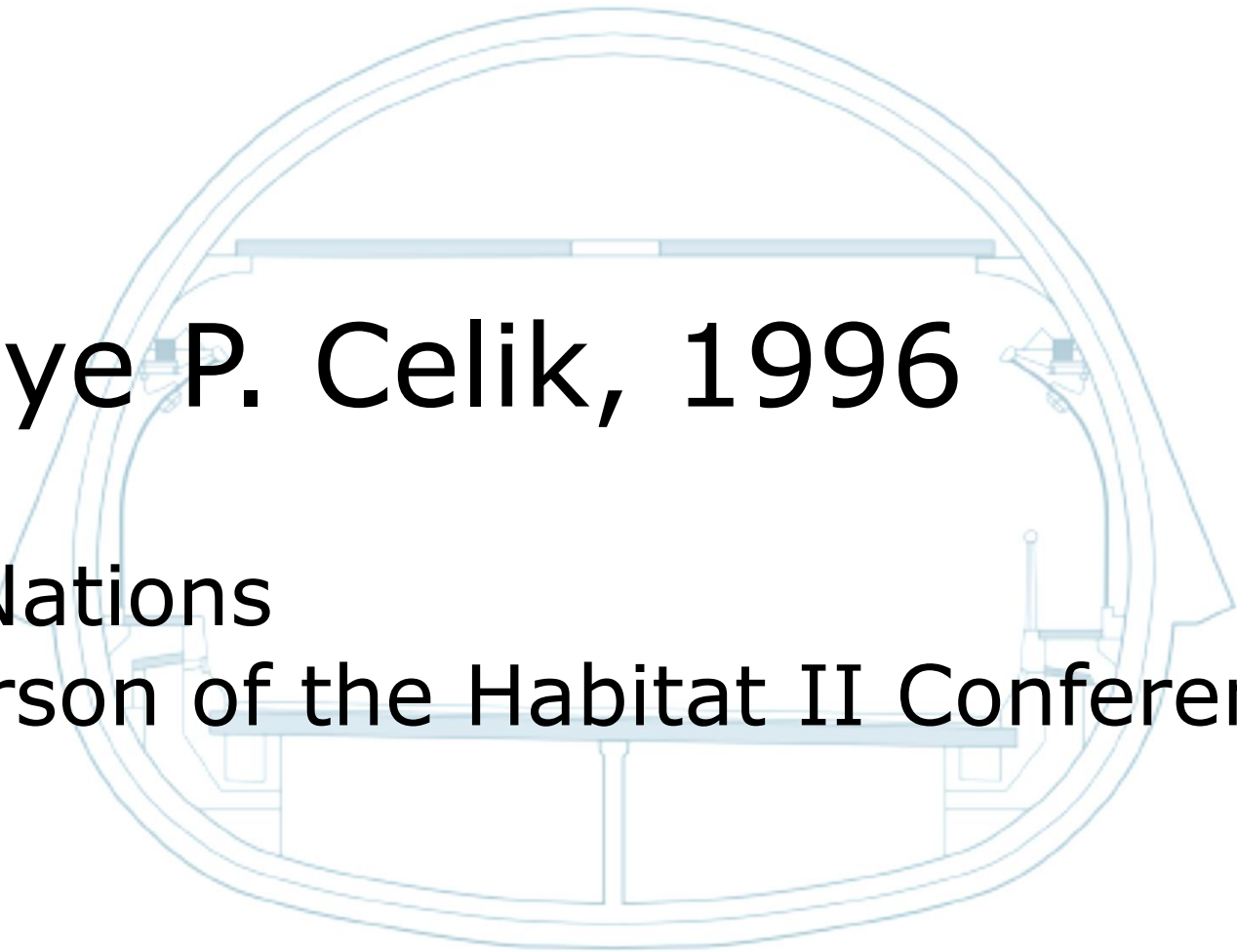
“... Tunnels will be a useful tool for water and energy supply, sewerage and transportation systems. Therefore, there will be a great challenge for underground systems and for economic solutions for infrastructure”.



Importância de túneis para infraestrutura urbana

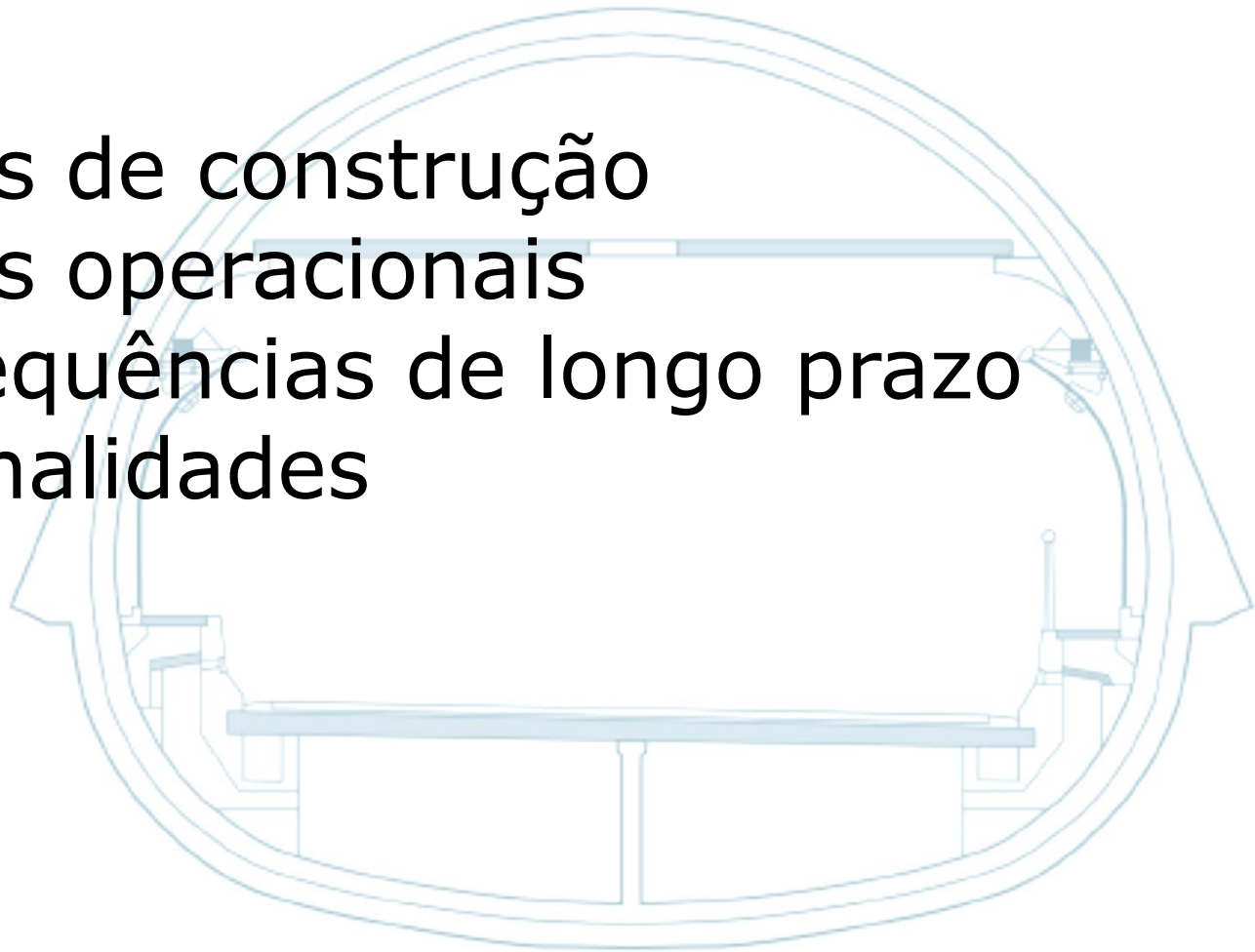
Dr. Aliye P. Celik, 1996

United Nations
Chairperson of the Habitat II Conference,
Istanbul



Avaliação de custos de obras subterrâneas

- Custos de construção
- Custos operacionais
- Consequências de longo prazo
- Externalidades



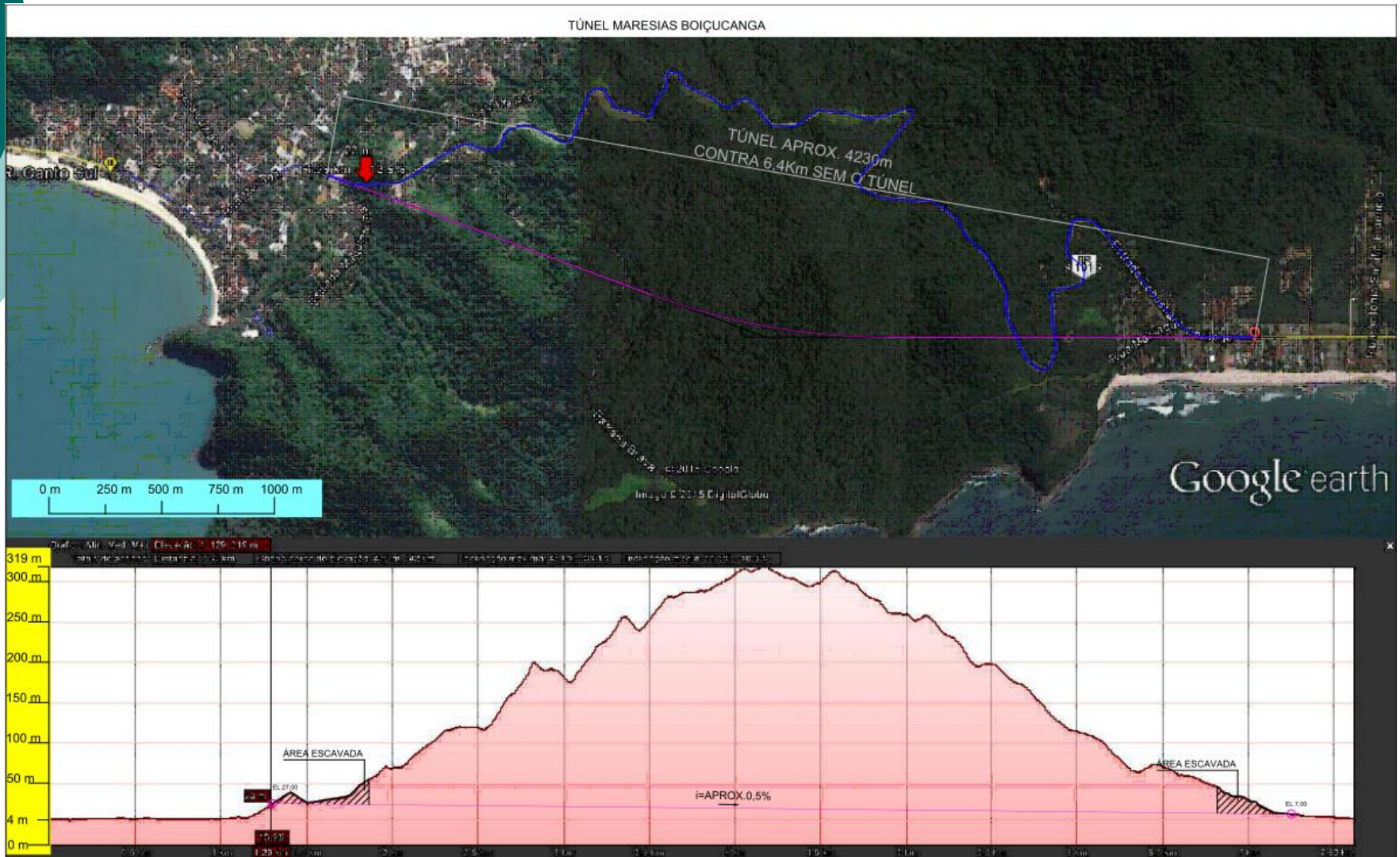
Example of externality cost evaluation

Exemplos de avaliação de custos de externalidades:

U.S. Congress Office of Technology Assessment

- **OTA 1993: produção de eletricidade**
- **OTA 1994: atividades de transporte**

Proposta Maresias-Boiçucanga



Proposta Maresias-Boiçucanga

Percurso em Túnel vs Superfície

Resultados:

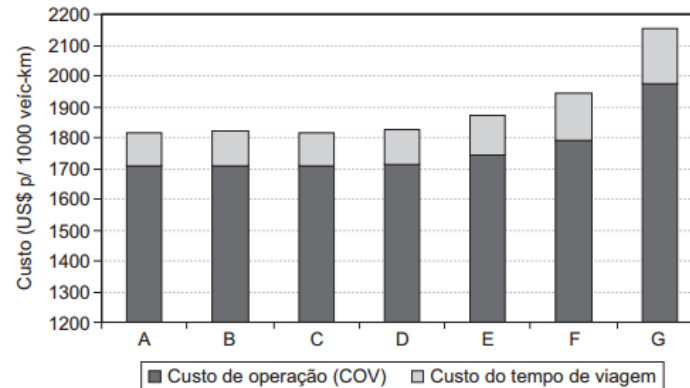
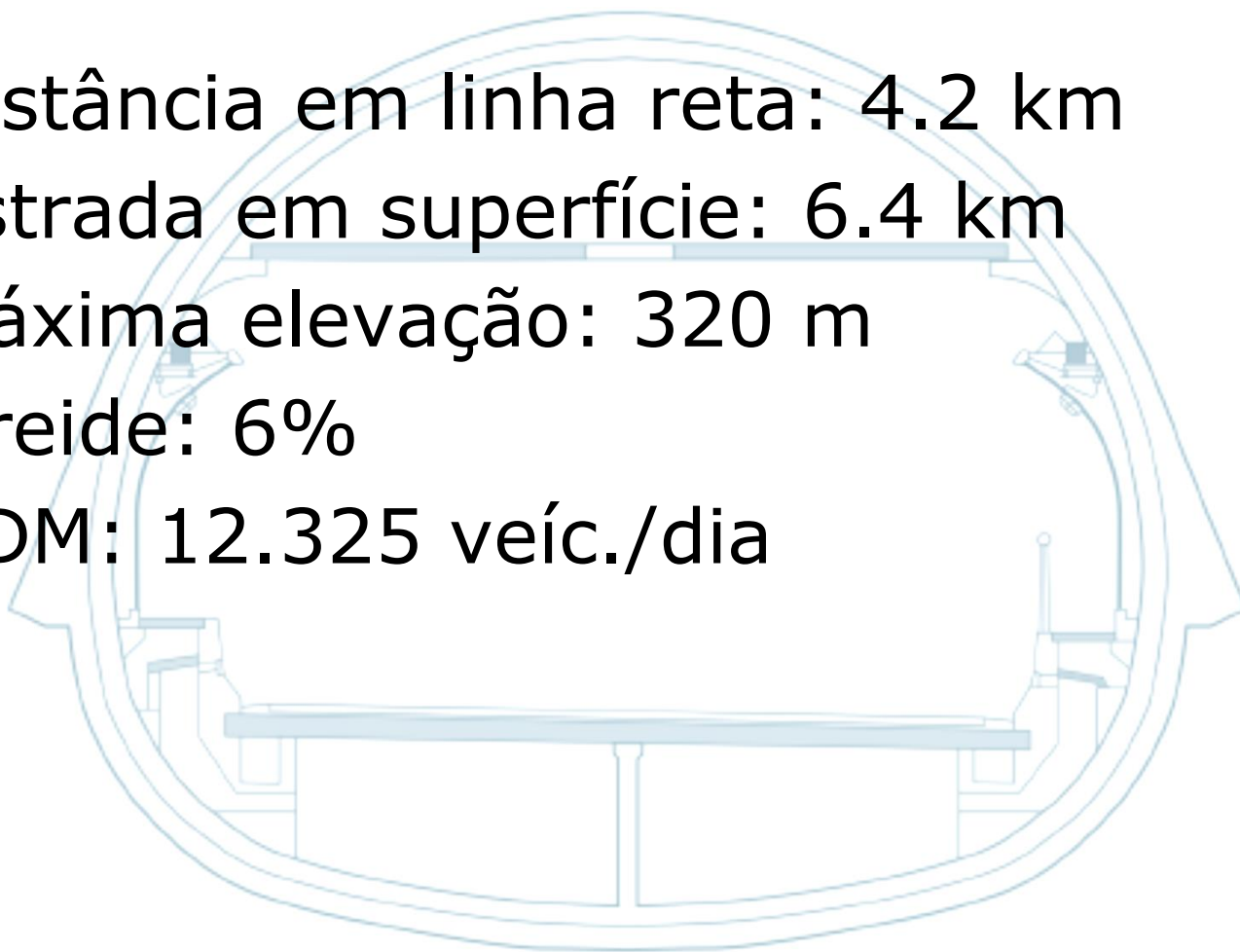


Figura 11 Custo total dos usuários dos trechos do HDM-4.

SP-55 – Maresias-Boiçucanga

- Distância em linha reta: 4.2 km
- Estrada em superfície: 6.4 km
- Máxima elevação: 320 m
- Greide: 6%
- VDM: 12.325 veíc./dia



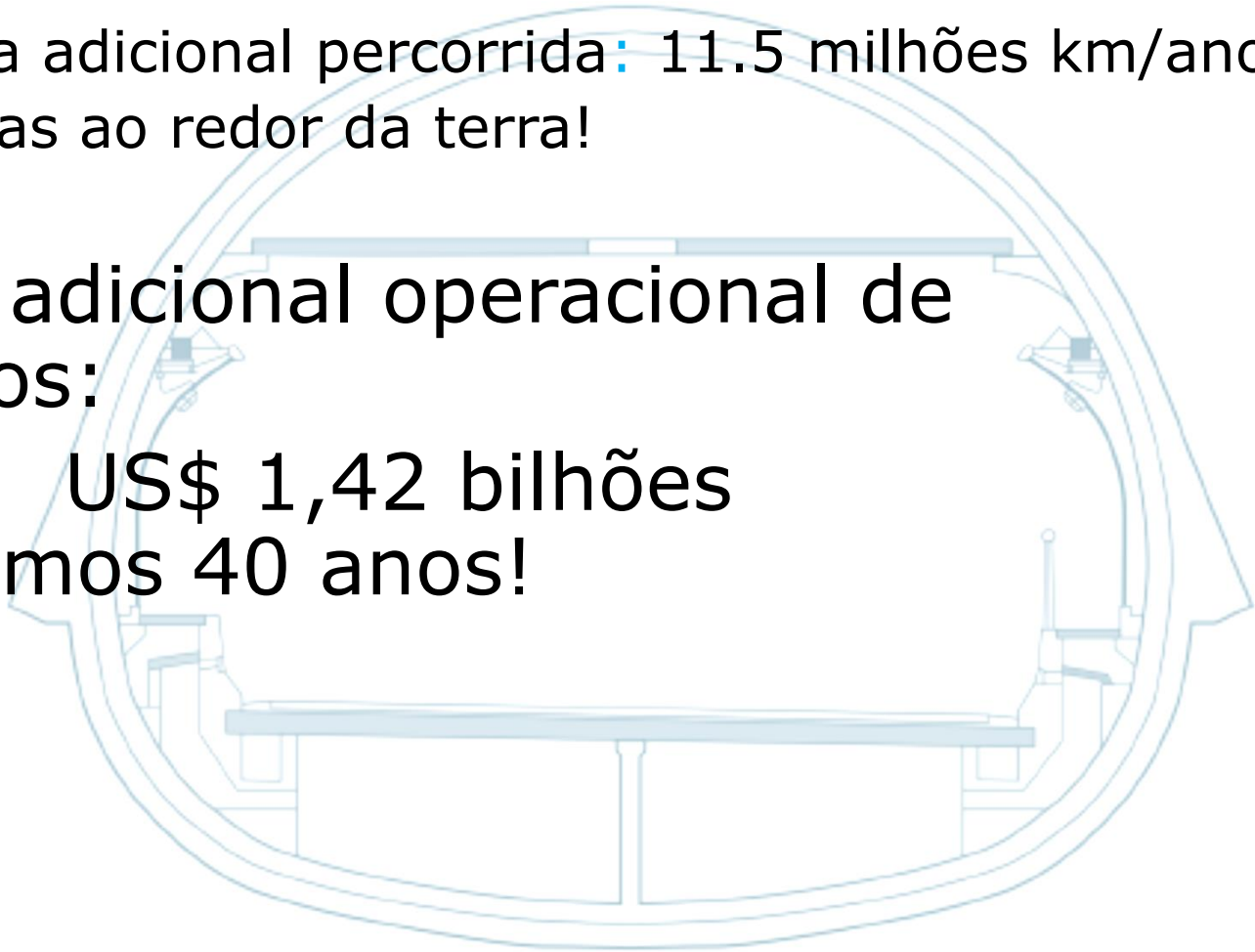
Custo operacional de veículos

Túnel vs superfície

- Distância adicional percorrida: 11.5 milhões km/ano
- 288 voltas ao redor da terra!

- Custo adicional operacional de veículos:

US\$ 1,42 bilhões
nos últimos 40 anos!



Elevados Urbanos

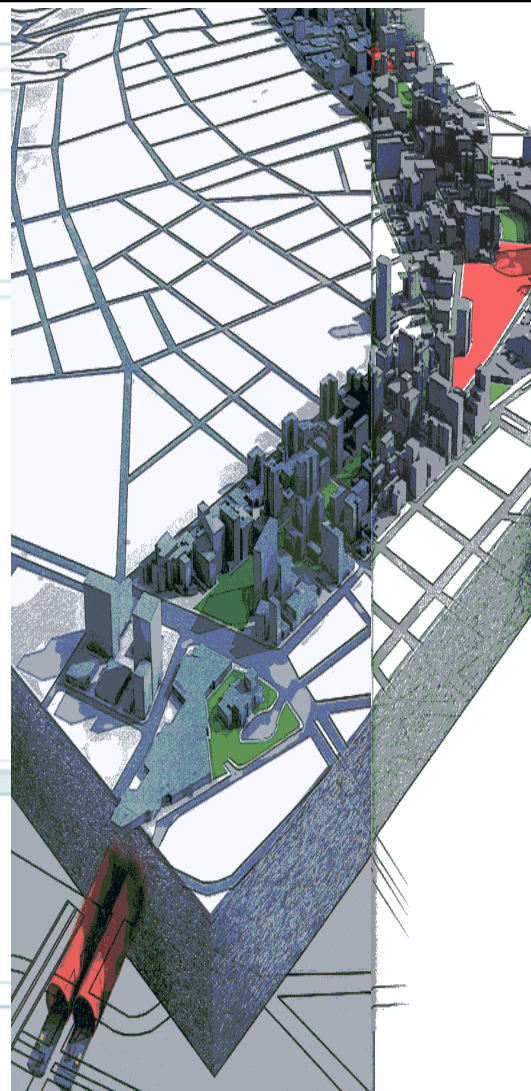
Degradação, Queda de IPTU, etc.



Elevado Costa & Silva, São Paulo



ABAIXO O ELEVADO!
Como tornar São Paulo uma cidade melhor







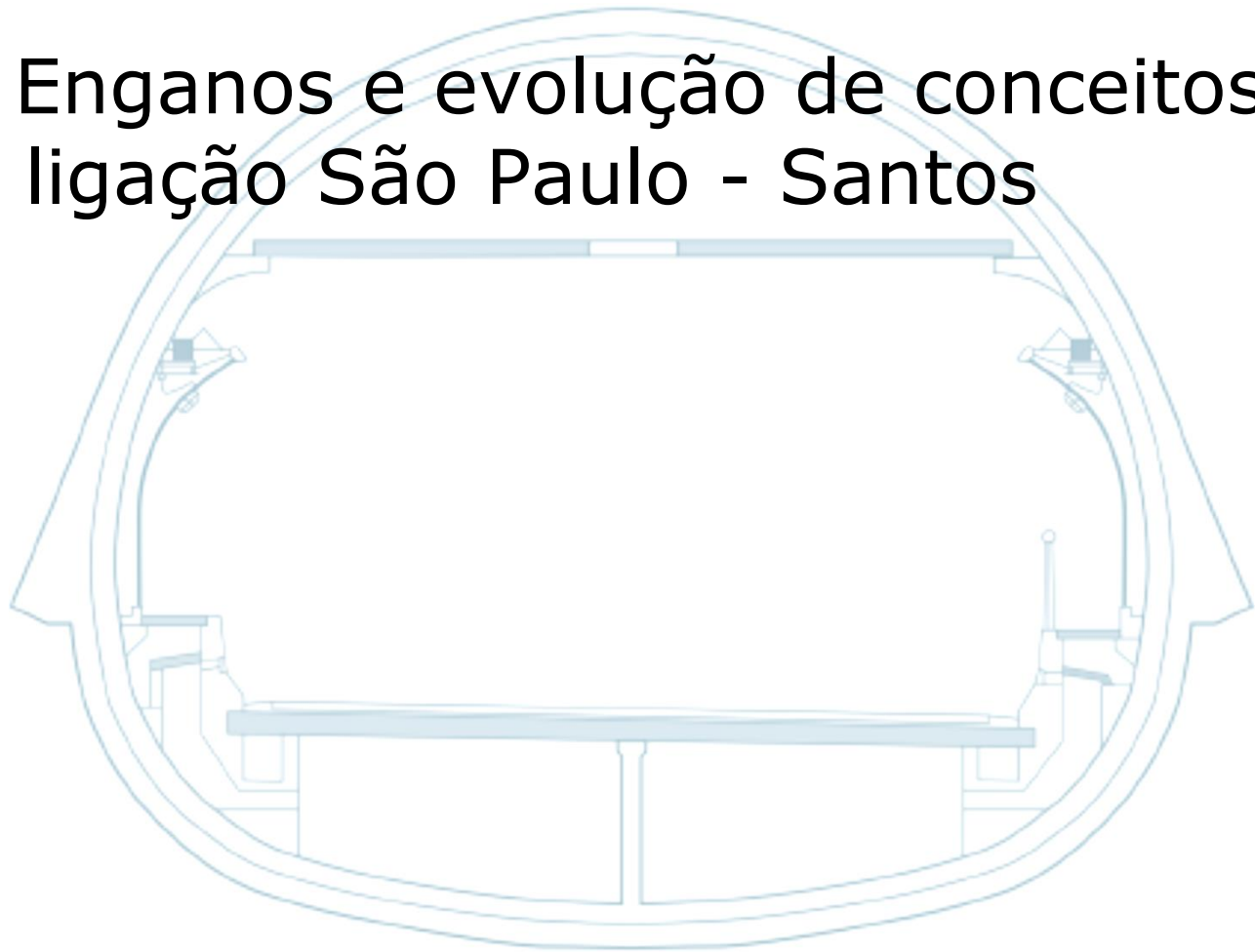
Google Street View



Oposição de ambientalistas brasileiros a obras subterrâneas

- Túnel sob o parque do Ibirapuera (“lago iria secar”)
- Reservatório subterrâneo de petróleo em São Sebastião (“explodir montanha”)
- Túnel do Rodoanel de São Paulo sob a Serra da Cantareira (“nuvem de fumaça sobre a serra”)
- Etc.

2- Enganos e evolução de conceitos na ligação São Paulo - Santos





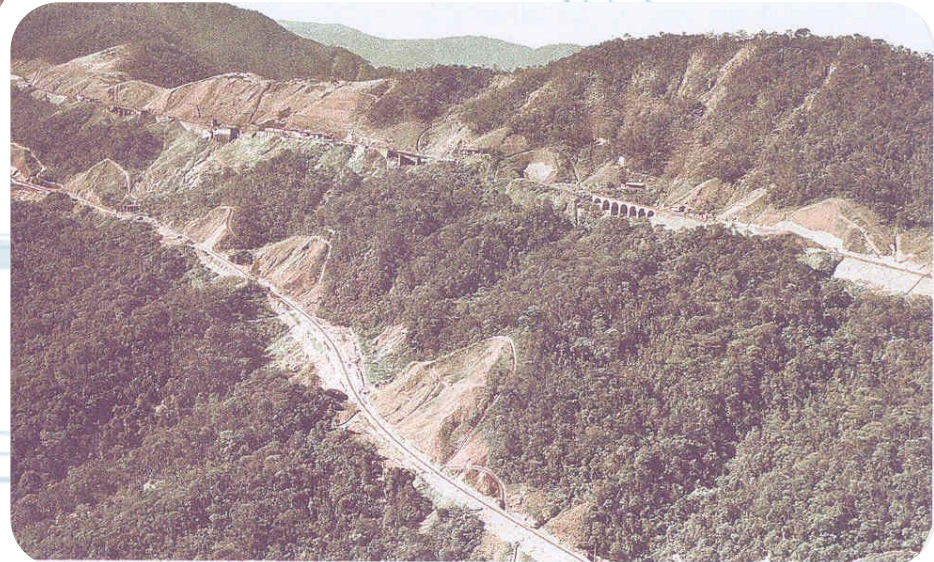
as das imagens: 26 de Abr de 2003 - 22 de Jun de 2007 23°53'27.05"S 46°26'42.04"O elev 8 m Altitude do ponto de

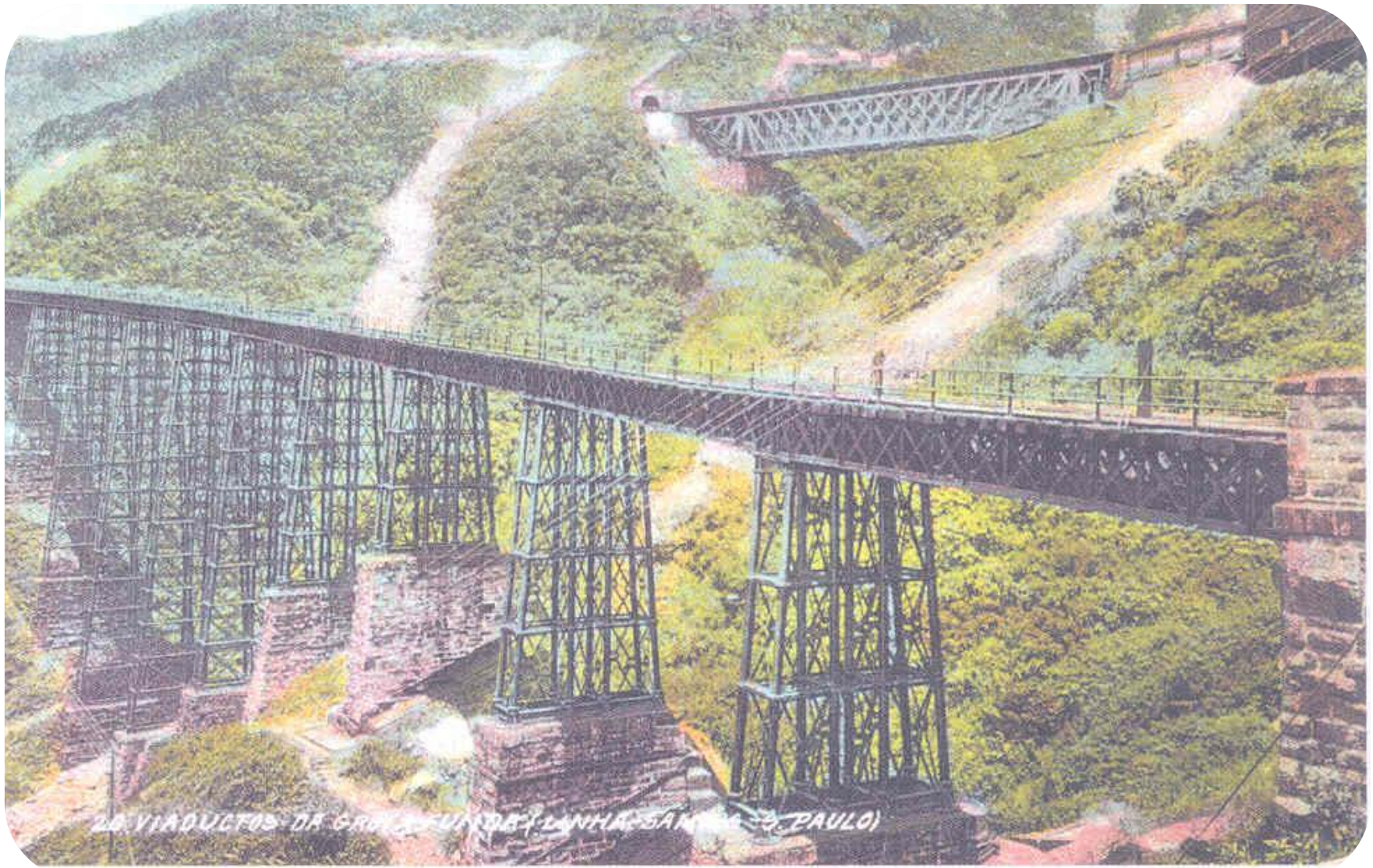




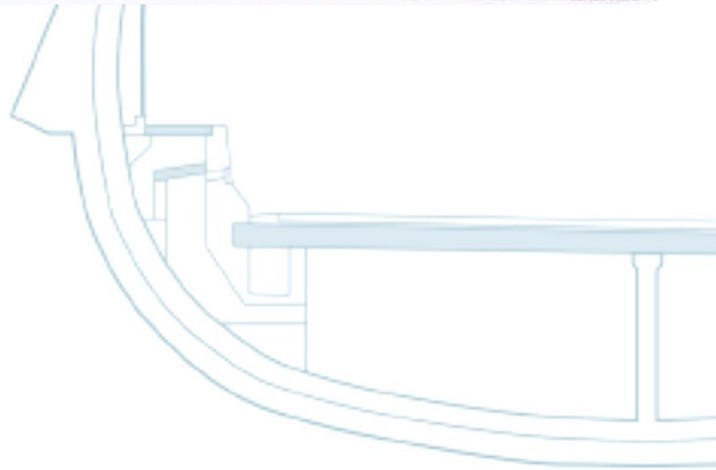
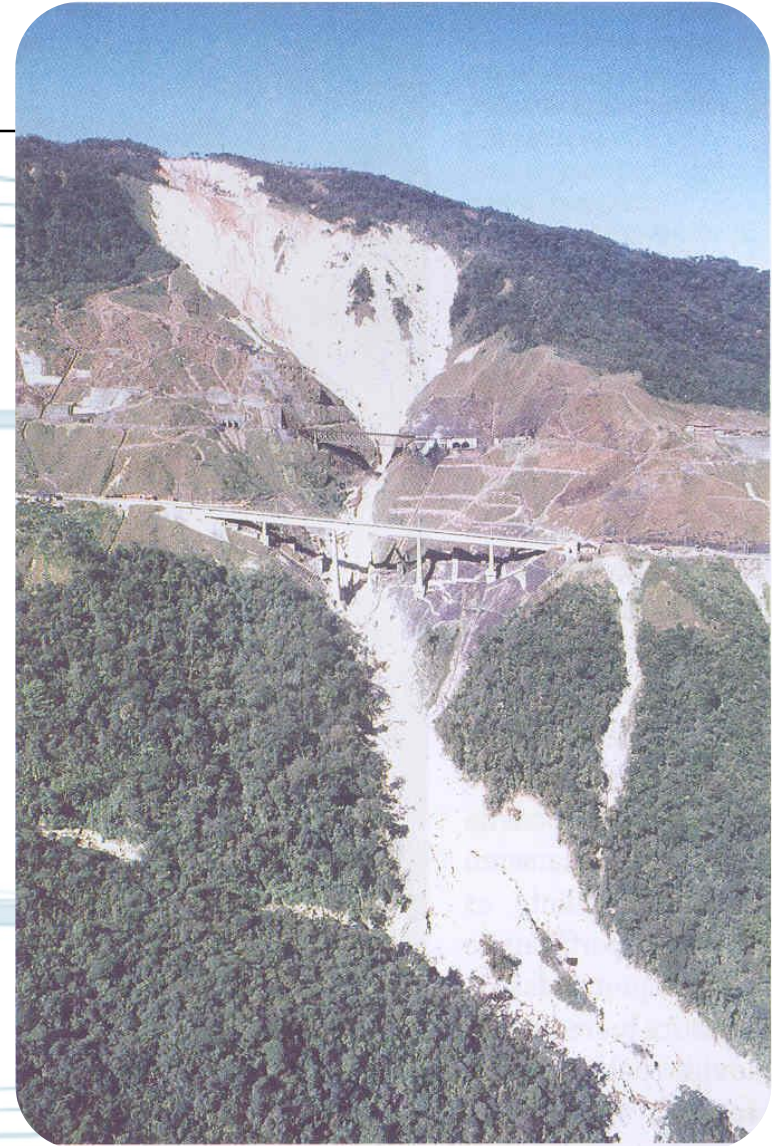
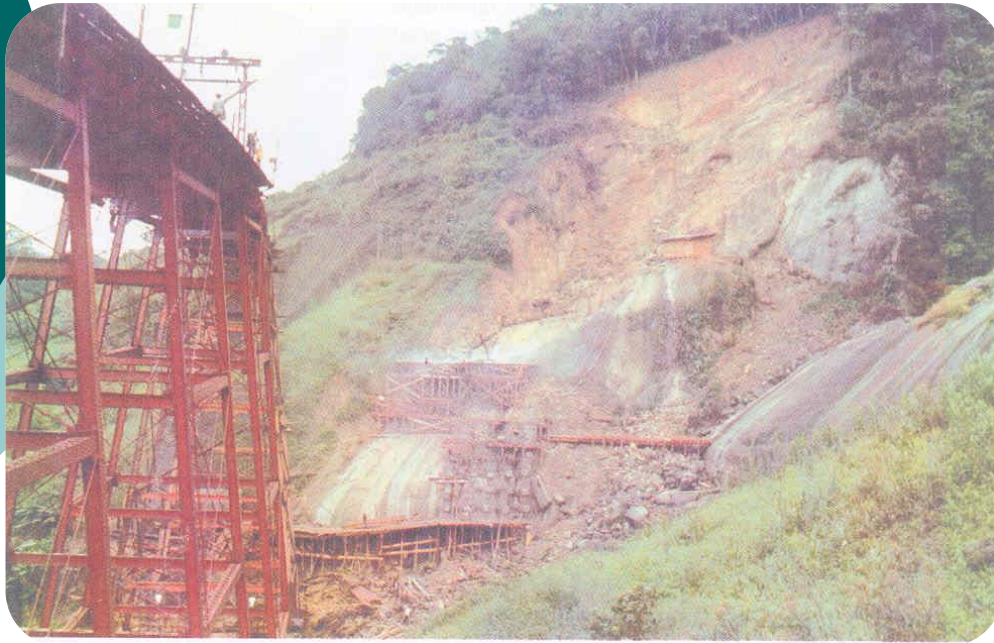


Ferrovias (1860 e 1900)

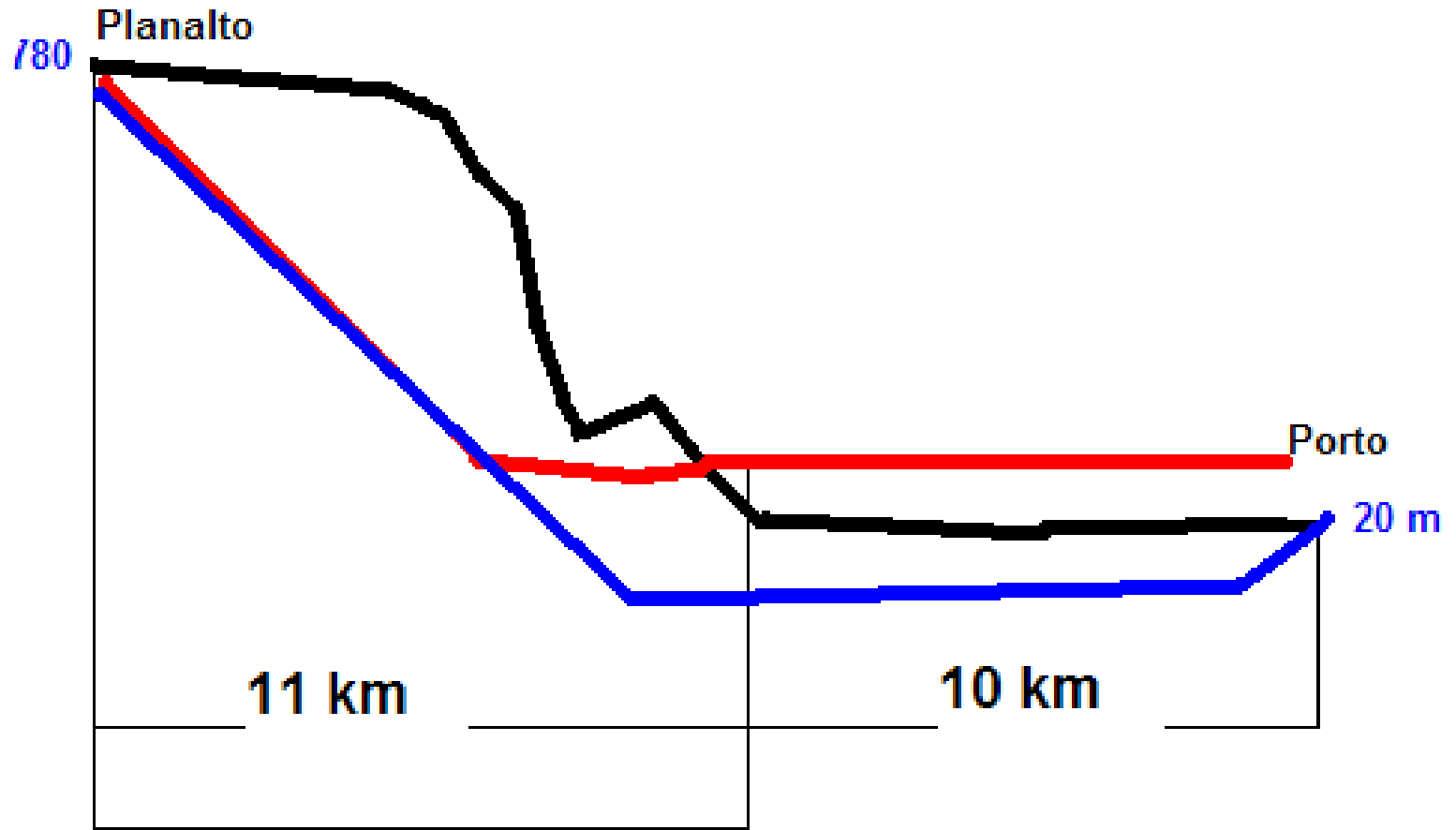




LE VIADUCTOS DA GRUBA-FUNDA (LINHAS SANTIAGO - S. PAULO)



Sistema Subterrâneo para Transporte de Containers



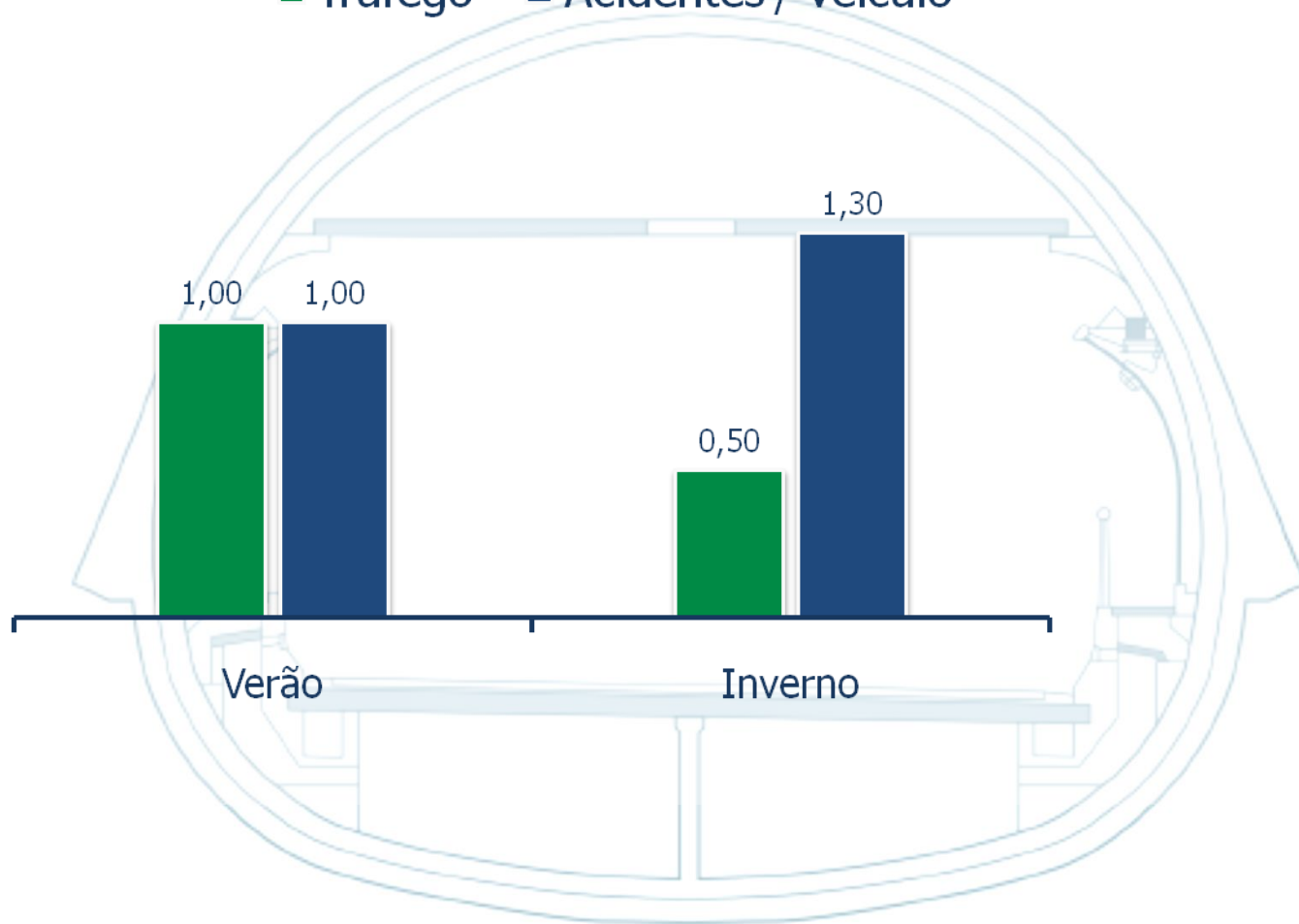
Sistema Subterrâneo para Transporte de Containers



Rodovia dos Imigrantes corrida de lama em 22 fev. 2013



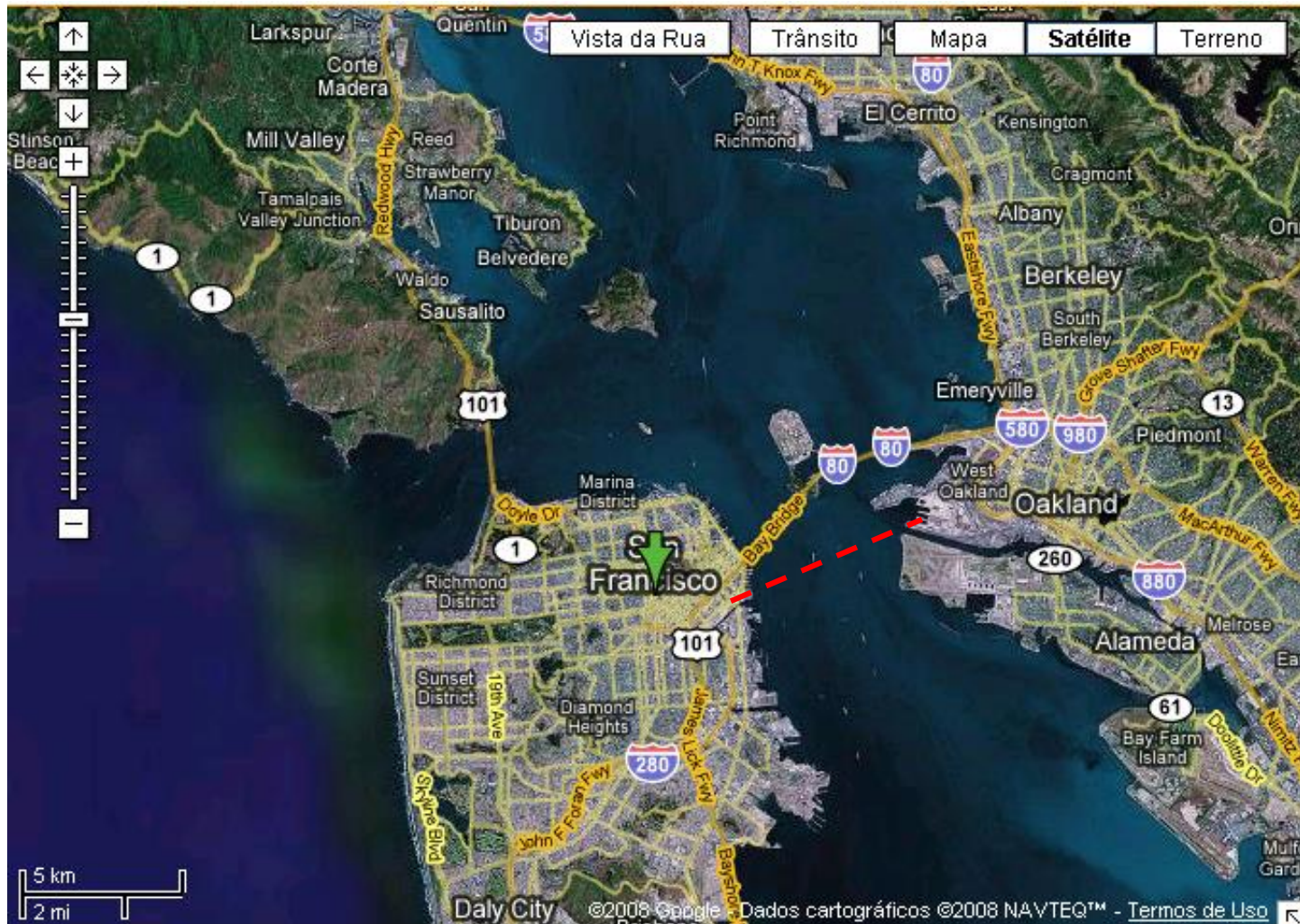
■ Tráfego ■ Acidentes / veículo



3 - Confiabilidade e segurança de túneis



Baía de San Francisco



Terremoto de Loma Prieta

17/10/1989

- Magnitude; 6,9 Richter
- Distância epicentro: 100 km
- Ponte (Bay Bridge): danos severos, colapso de um tramo, 69 mortos
- Túnel: voltou a operar 24 horas depois de vistoria; trem trafegando no túnel no momento do terremoto, ninguém percebeu

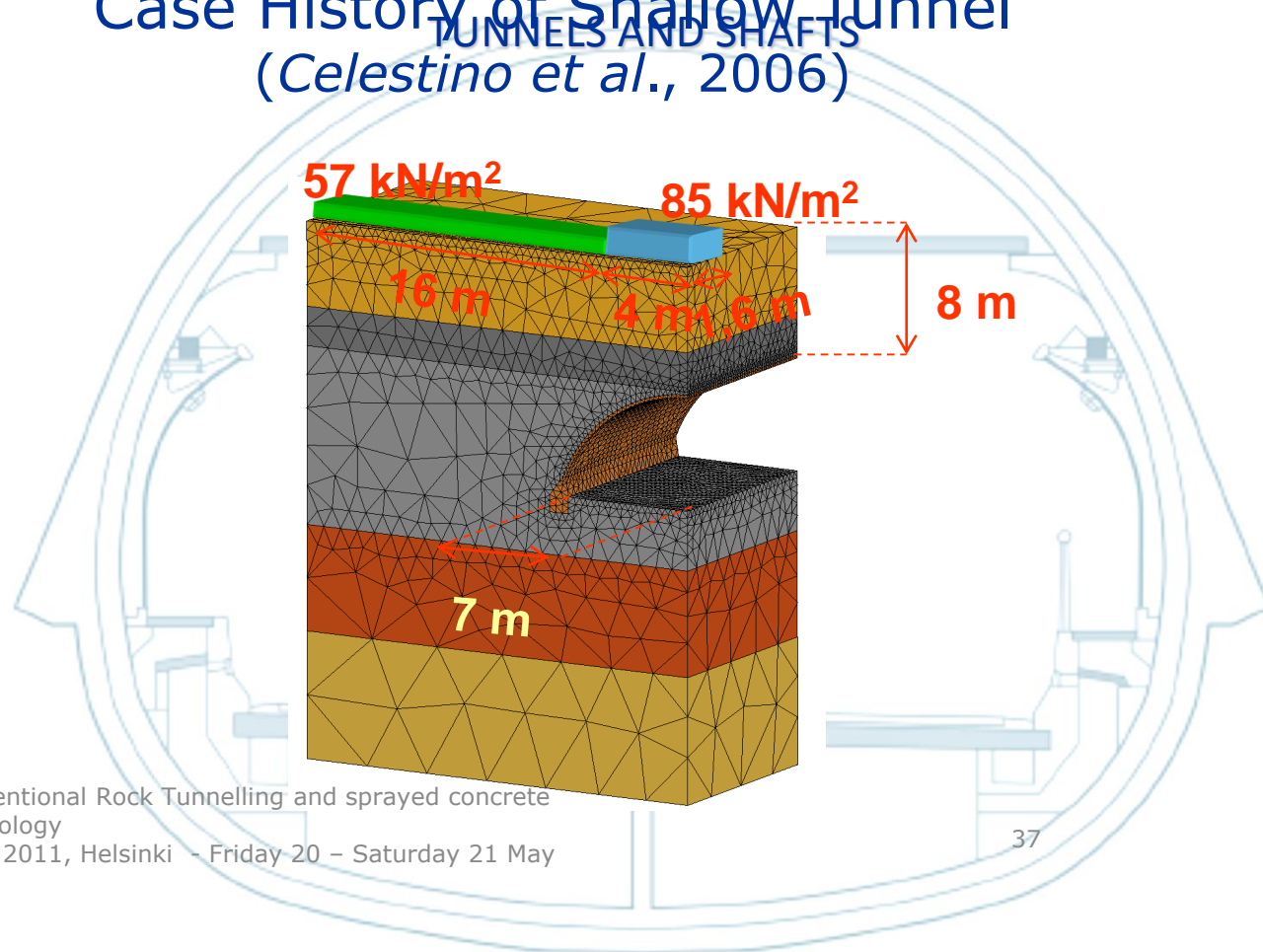
Terremoto de Loma Prieta

17/10/1989

Danos na Ponte – 69 mortos



Case History of Shallow Tunnel (Celestino et al., 2006)



Conventional Rock Tunneling and sprayed concrete
technology
WTC 2011, Helsinki - Friday 20 - Saturday 21 May
2011

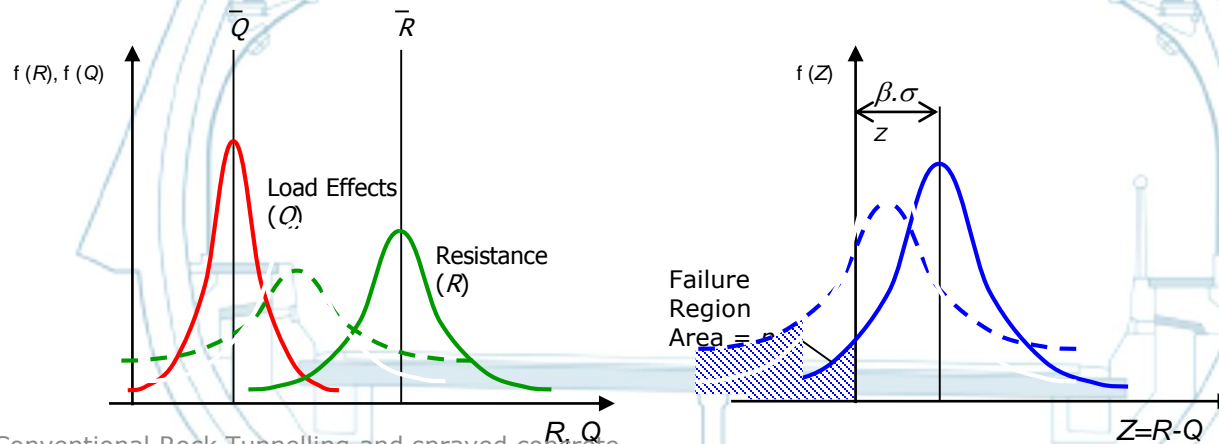
Probability Density Functions Load and Resistance Factor Design

$$FS = \frac{\bar{R}}{\bar{Q}}$$

$$\beta = \frac{\bar{R} - \bar{Q}}{\sqrt{\sigma_R^2 + \sigma_Q^2}}$$

$$\beta = \frac{\bar{R} \left[1 - \frac{1}{FS} \right]}{\sqrt{\sigma_R^2 + \sigma_Q^2}}$$

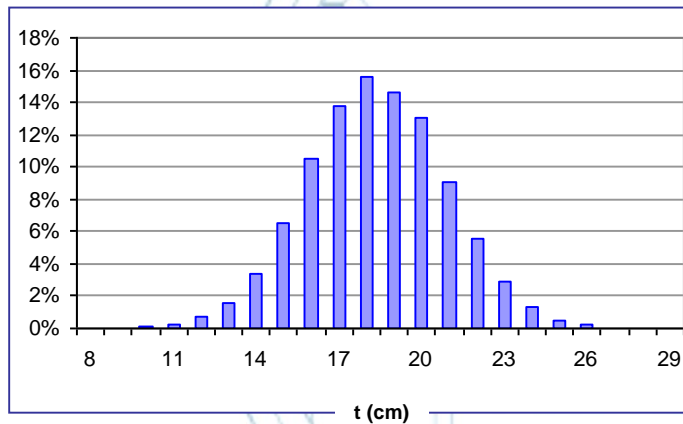
Load effects and resistance Margin of safety $Z = R - Q$



Resistance Histograms

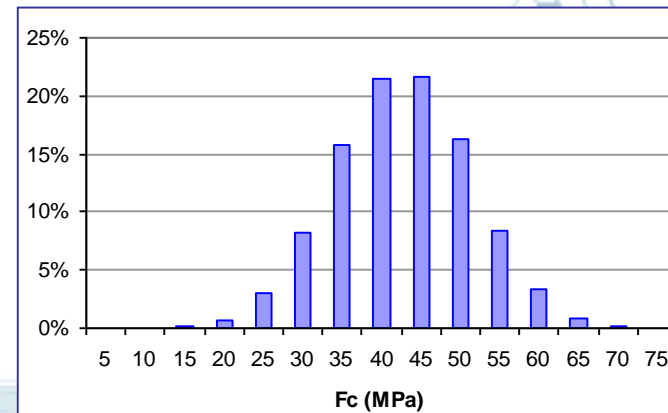
Thickness

$\bar{t} = 19.5 \text{ cm}$
c.v. = 14,3 %

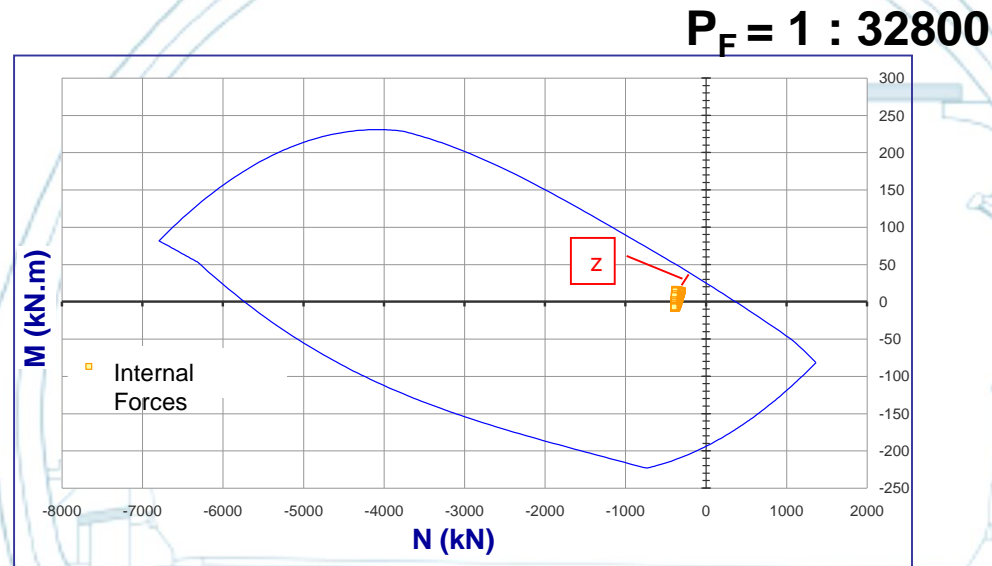


fc

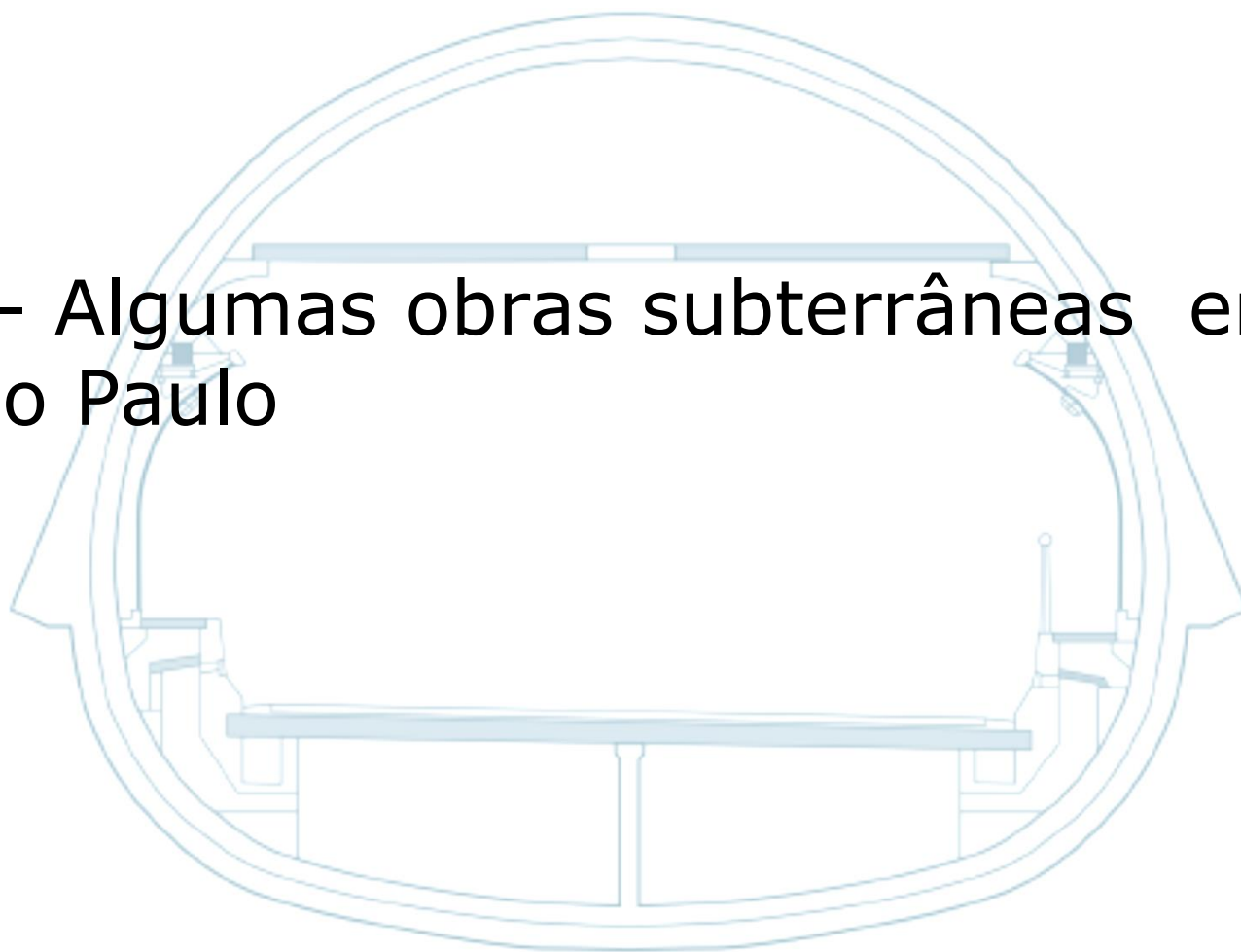
$\bar{f}_c = 40.1 \text{ MPa}$
c.v. = 25,5 %



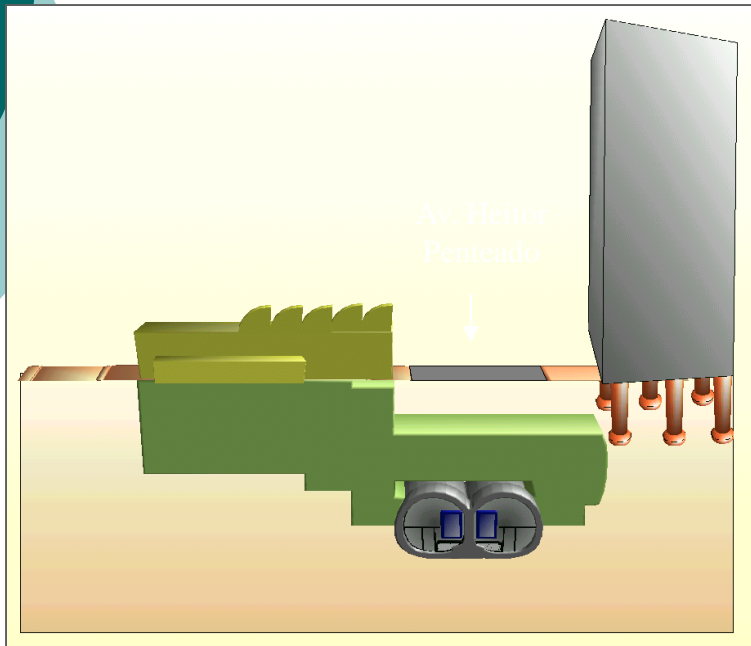
Moment-thrust Interaction Diagrams (Generated with Monte Carlo Simulation)



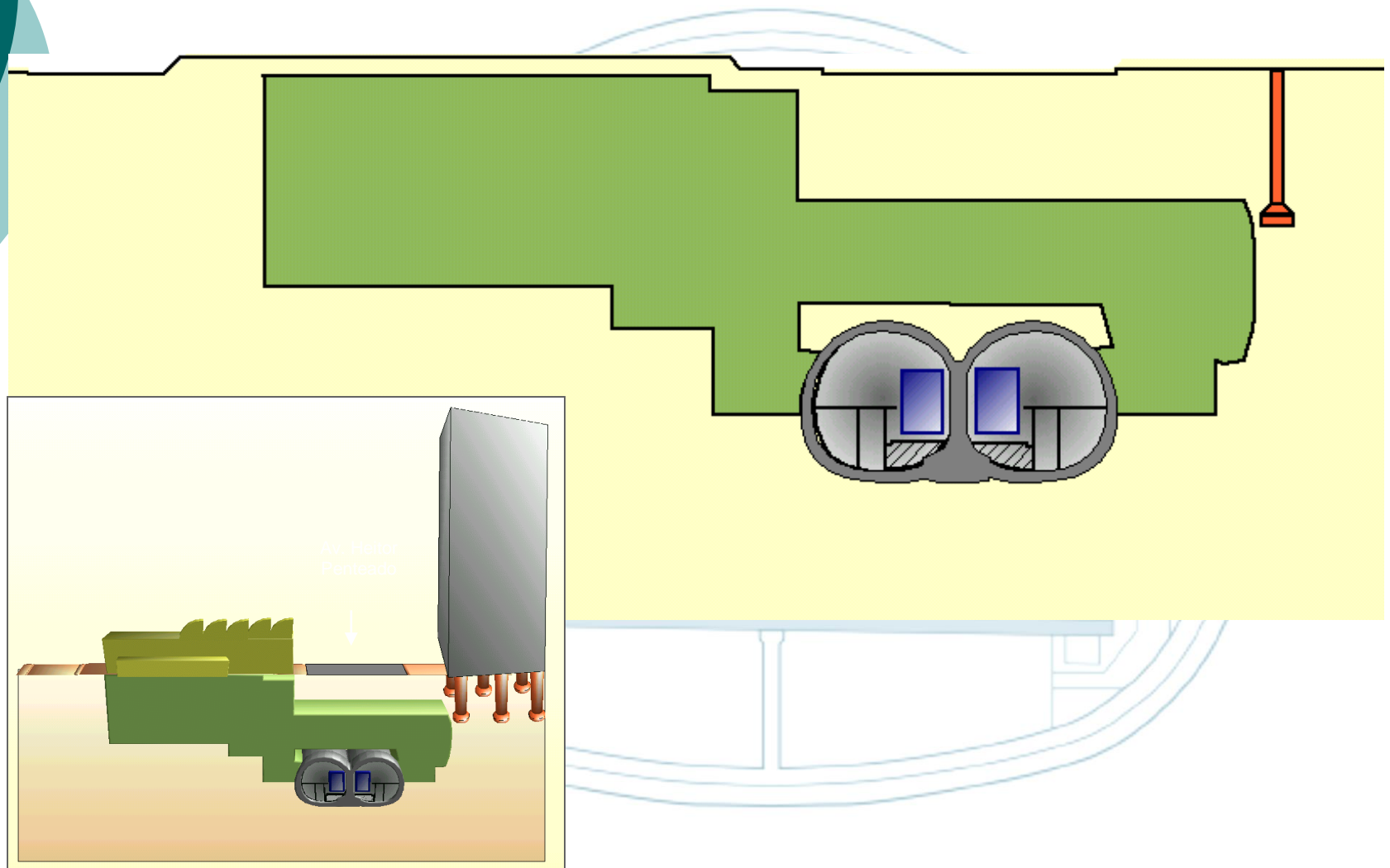
4 – Algumas obras subterrâneas em São Paulo



Metrô – Estação Vila Madalena



Metrô – Estação Vila Madalena



Shafts

Braced Excavation or Sprayed Concrete Shafts

– 1970s

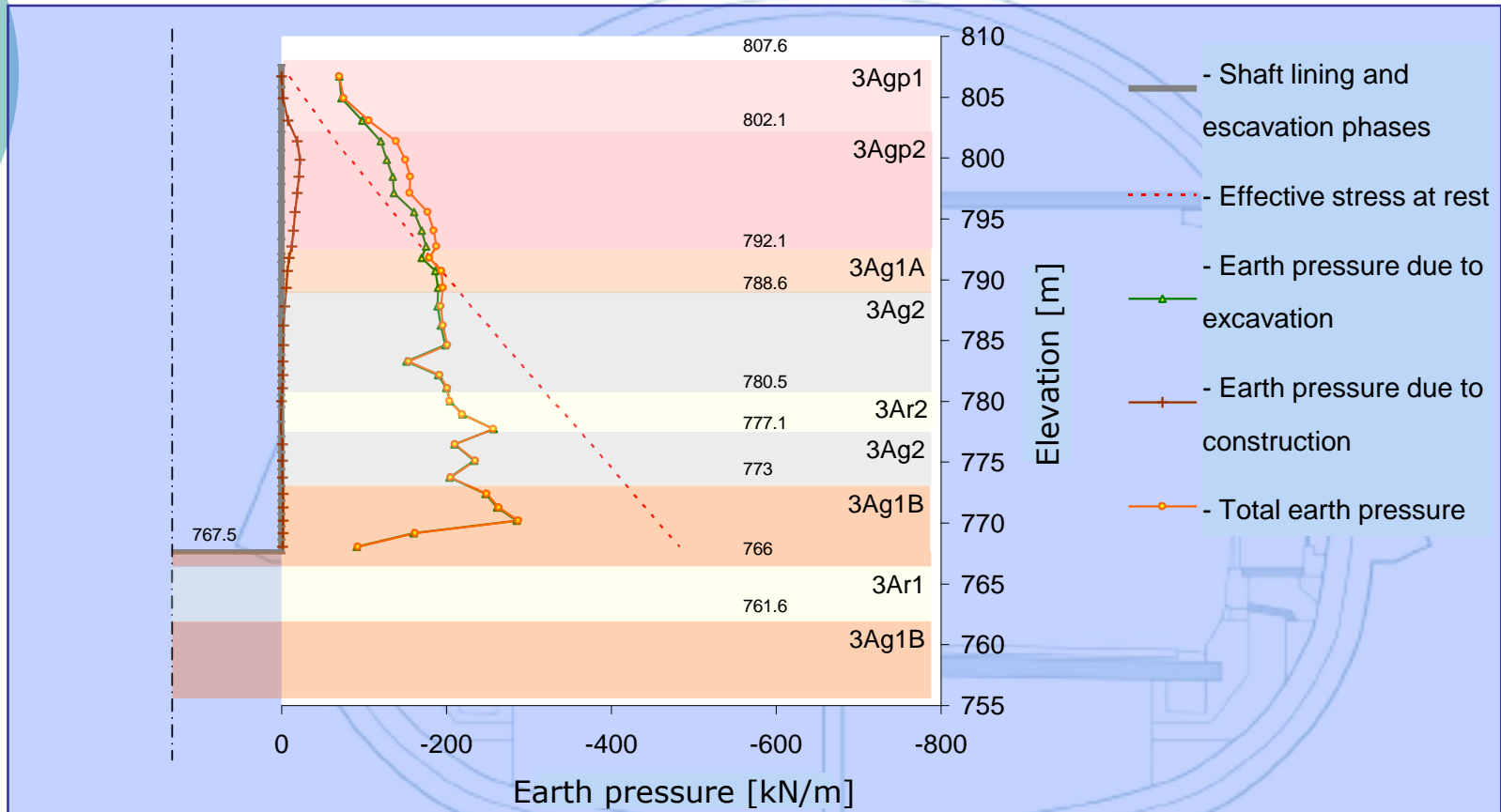


Shotcrete for shaft support

José Eusébio Shaft, São Paulo Line 4



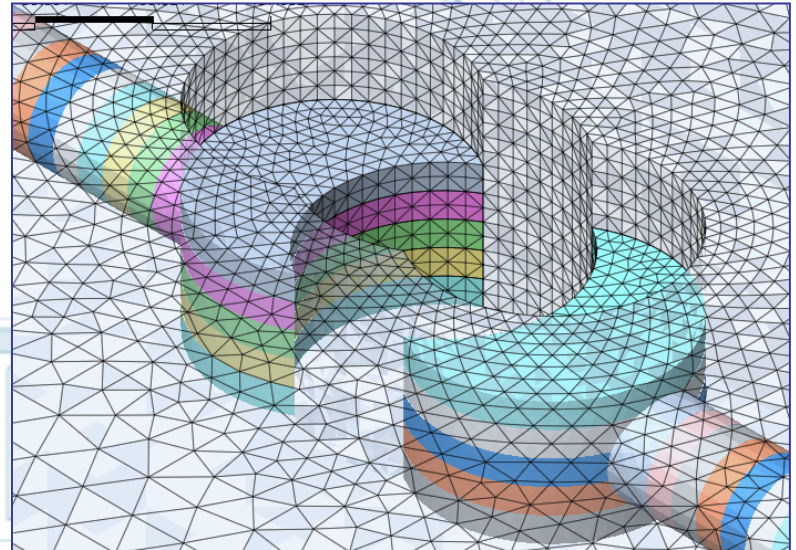
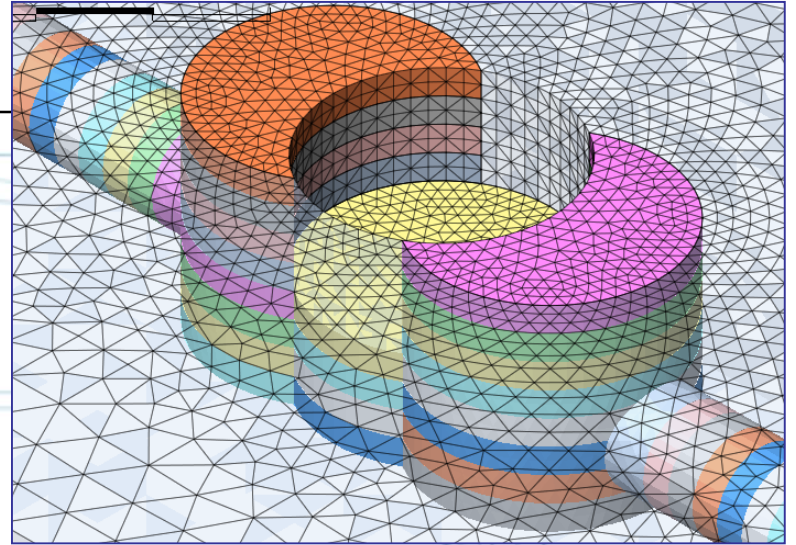
José Eusébio Shaft

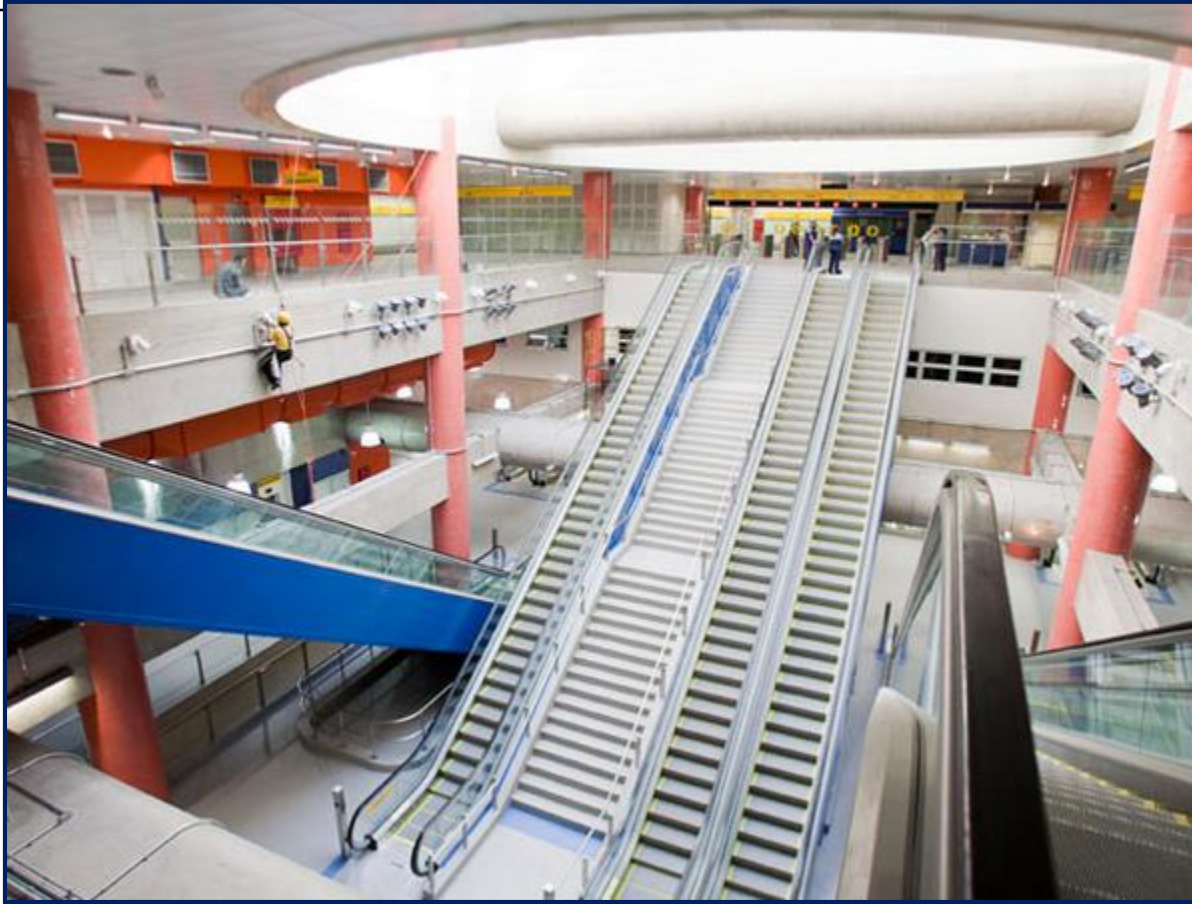


São Paulo Metro Luz Station Shaft



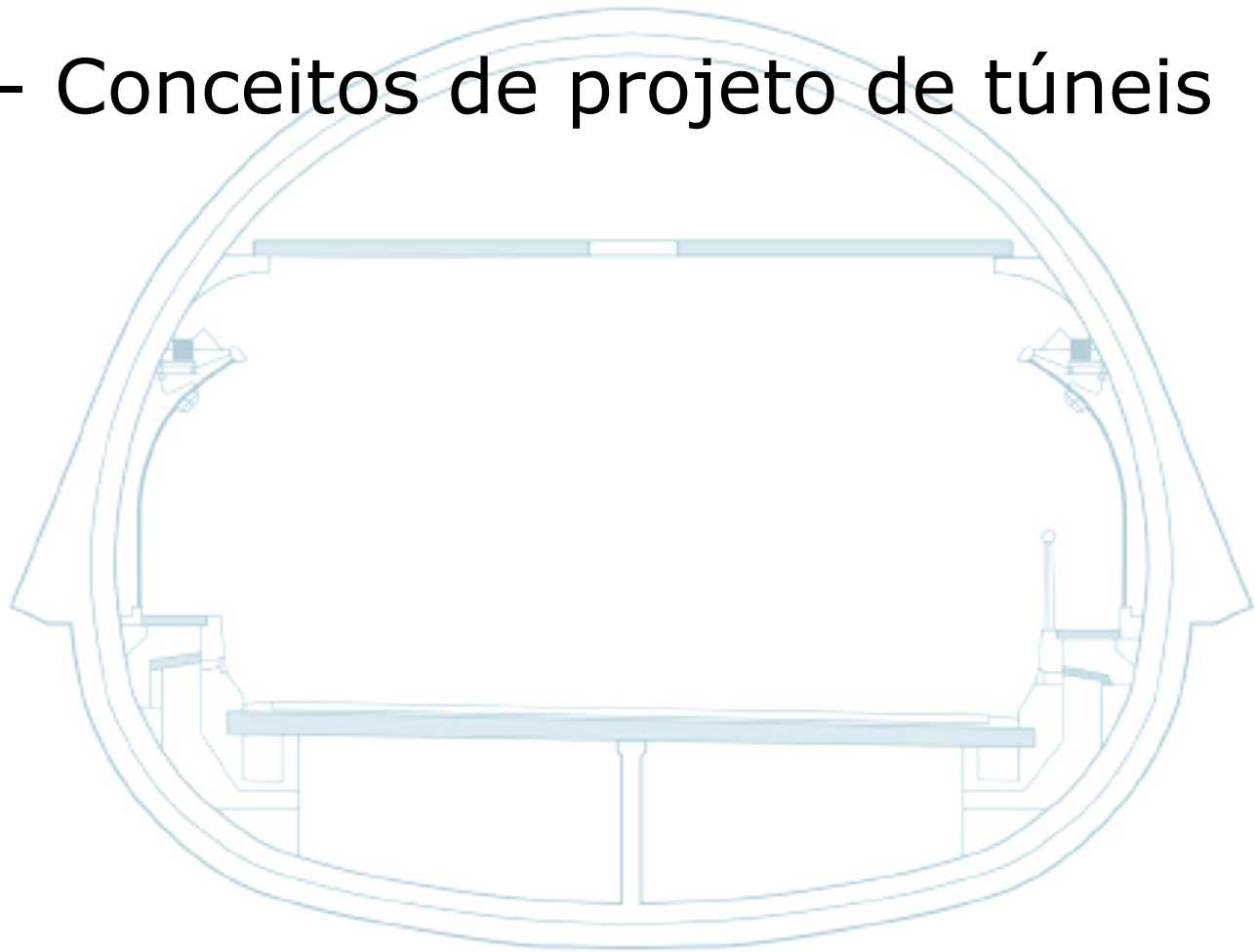
3D simulation







5 – Conceitos de projeto de túneis

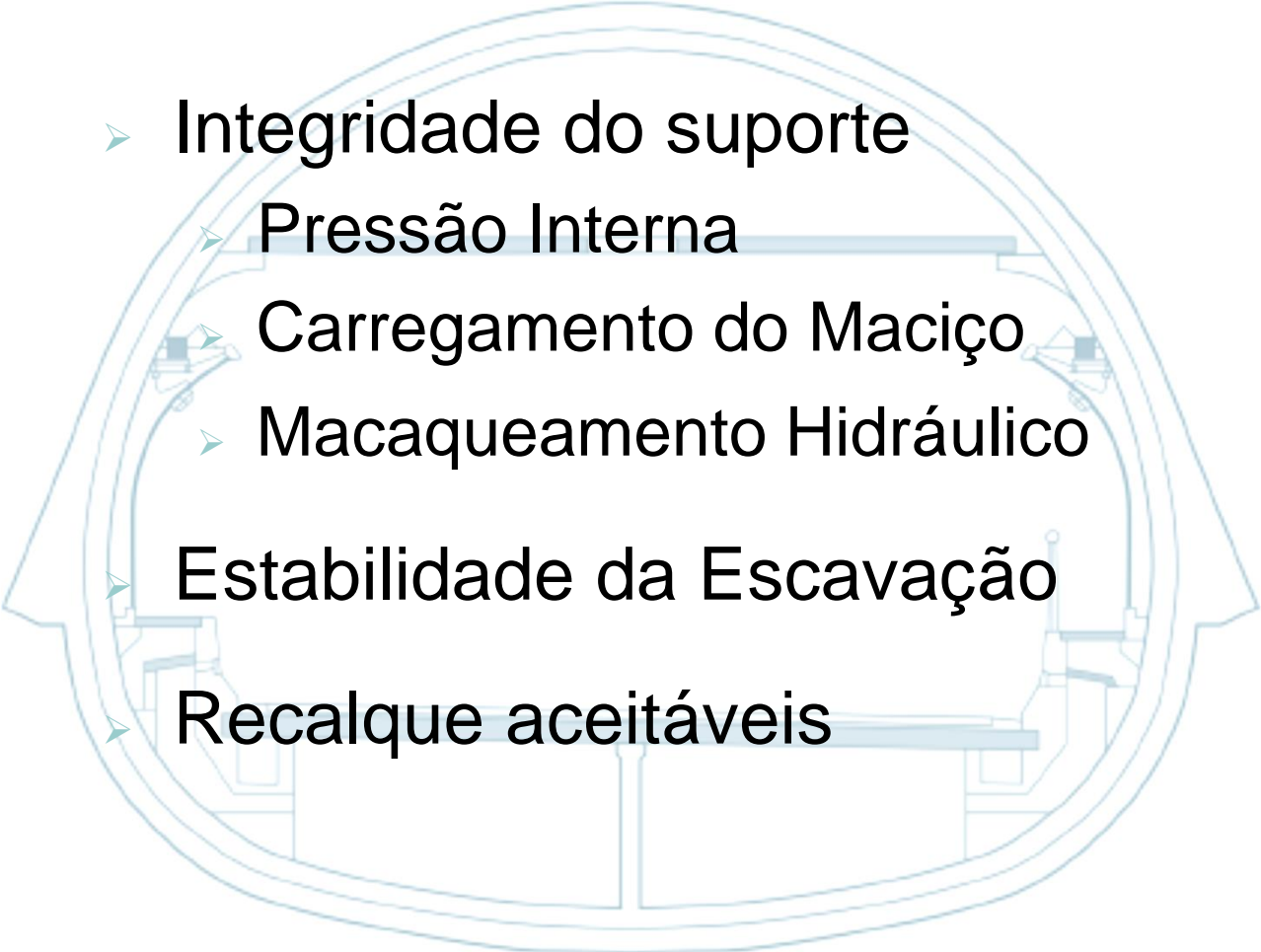




Métodos de Projeto

- Empíricos (Classificações Geomecânicas)
- Semi-Empíricos
- Observacionais
- Rigorosos

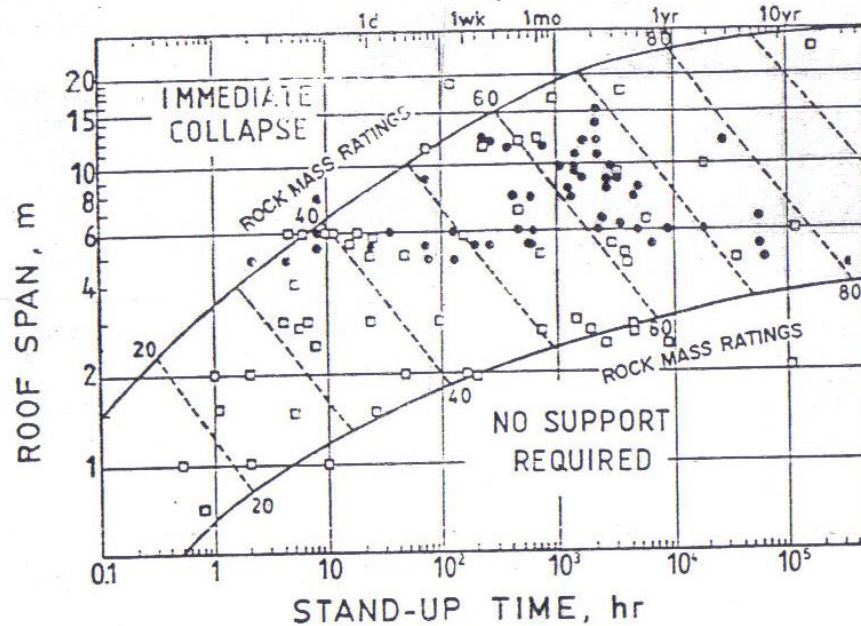
Pontos para Projeto

- 
- ▶ Integridade do suporte
 - ▶ Pressão Interna
 - ▶ Carregamento do Maciço
 - ▶ Macaqueamento Hidráulico
 - ▶ Estabilidade da Escavação
 - ▶ Recalque aceitáveis

Métodos Empíricos – Bieniawski

Tempo de auto-sustentação

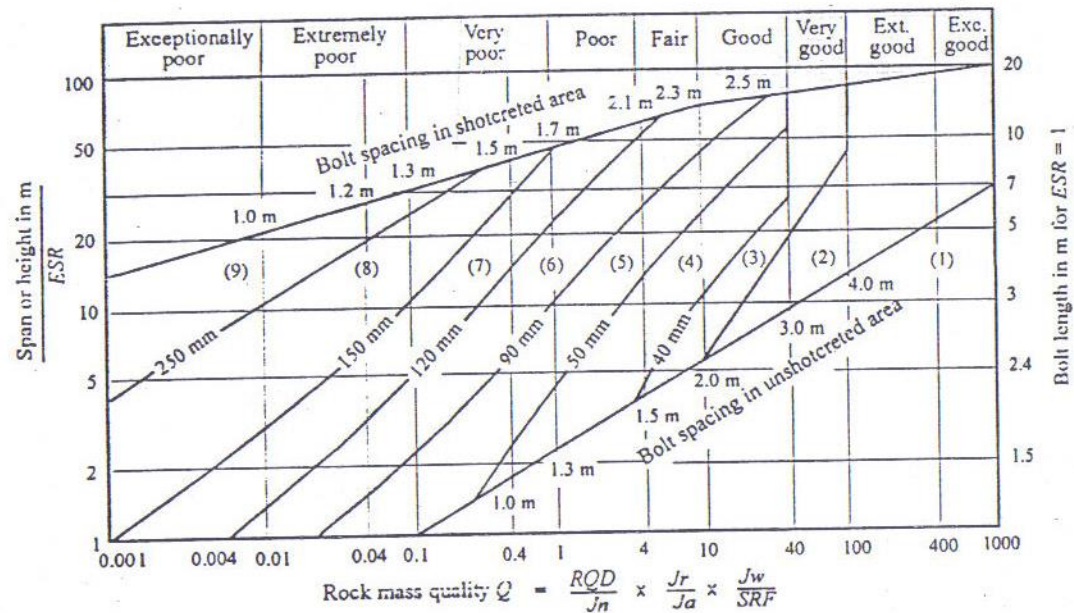
Geomechanics Classification (RMR system) 113



$$p = \frac{100 - RMR}{100} \gamma B$$

Métodos empíricos - Barton

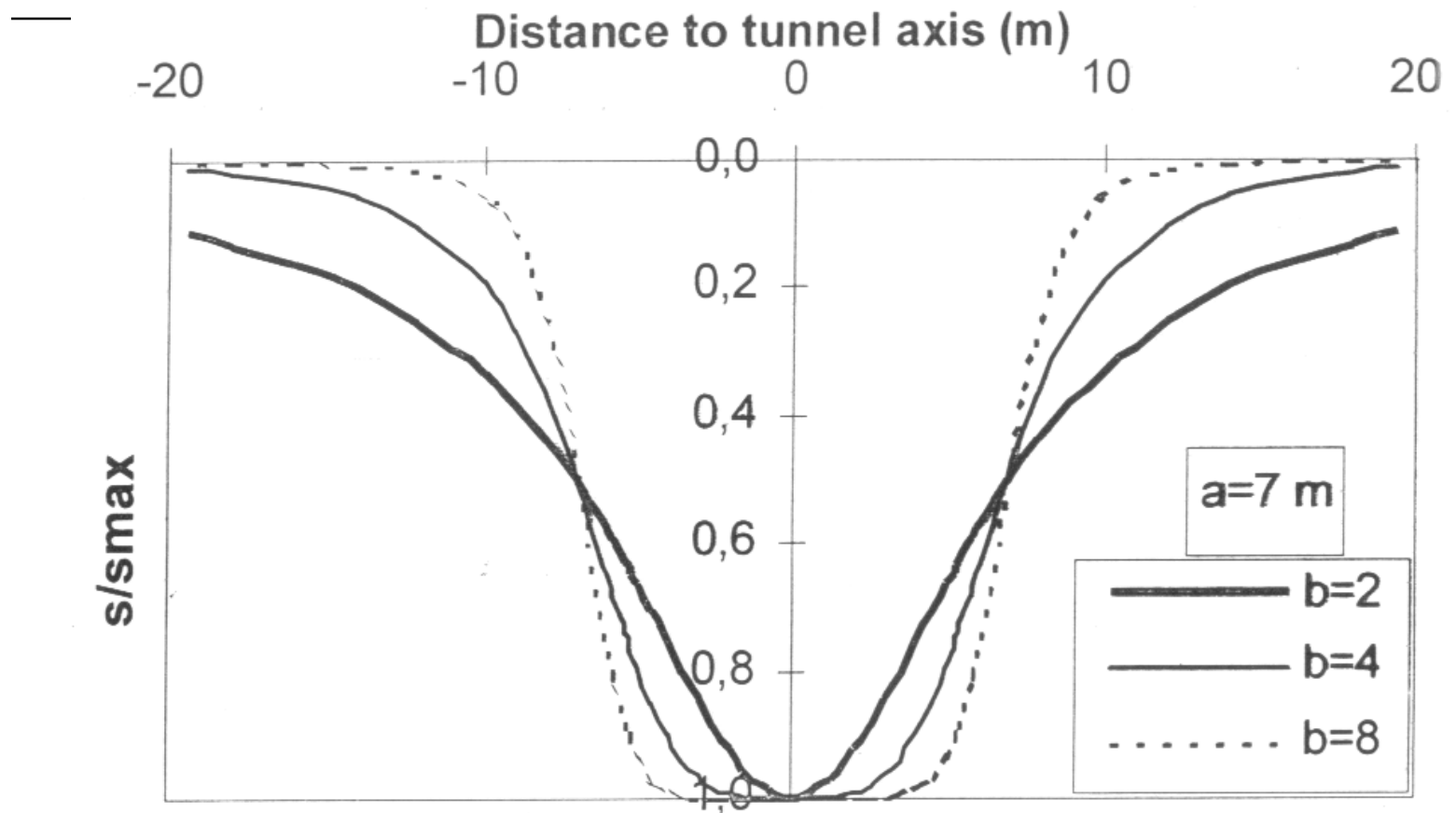
Estimativa de suporte



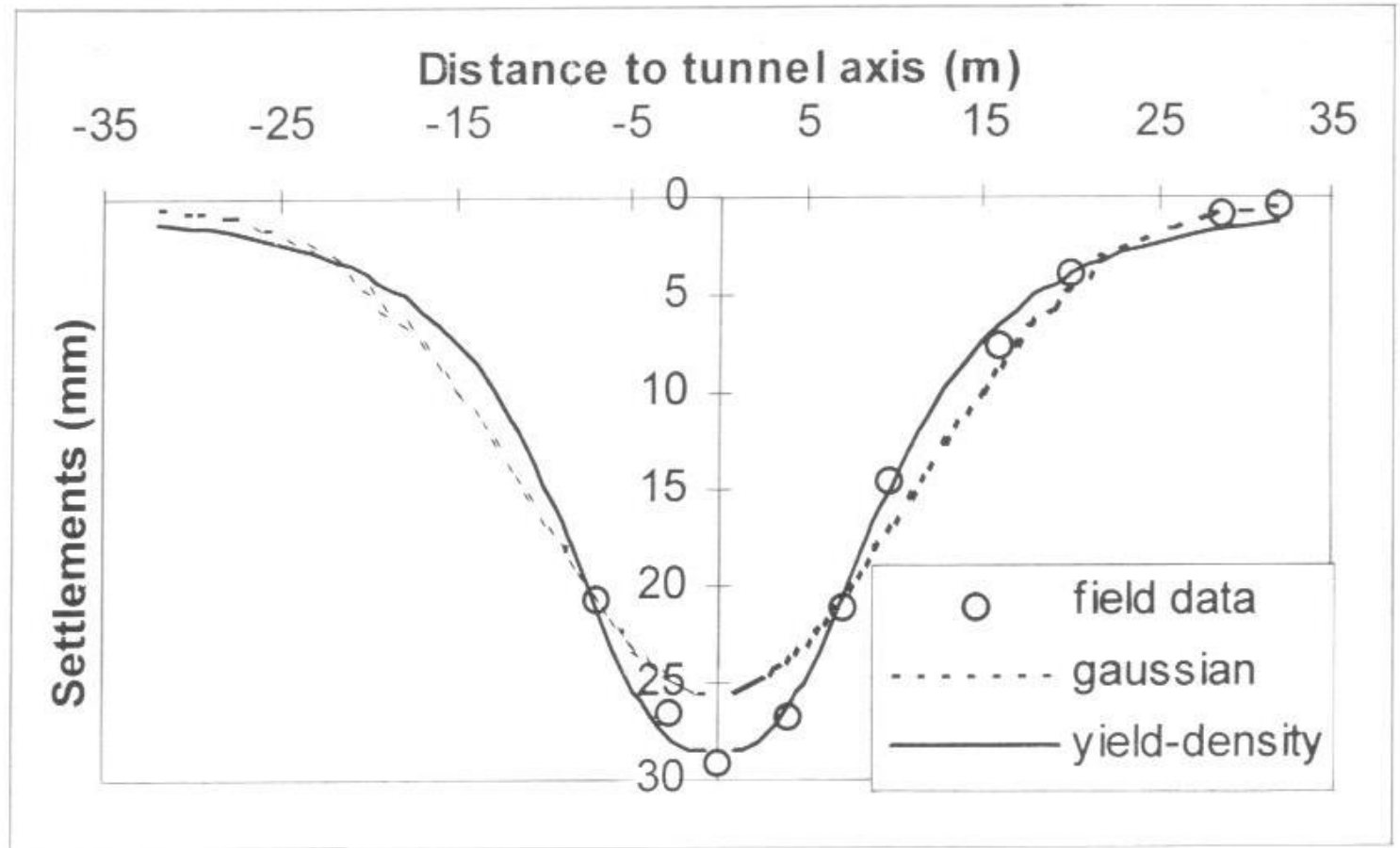
REINFORCEMENT CATEGORIES

- | | |
|---|---|
| <ul style="list-style-type: none"> 1) Unsupported 2) Spot bolting 3) Systematic bolting 4) Systematic bolting with 40-100 mm unreinforced shotcrete | <ul style="list-style-type: none"> 5) Fibre reinforced shotcrete, 50 - 90 mm, and bolting 6) Fibre reinforced shotcrete, 90 - 120 mm, and bolting 7) Fibre reinforced shotcrete, 120 - 150 mm, and bolting 8) Fibre reinforced shotcrete, > 150 mm, with reinforced ribs of shotcrete and bolting 9) Cast concrete lining |
|---|---|

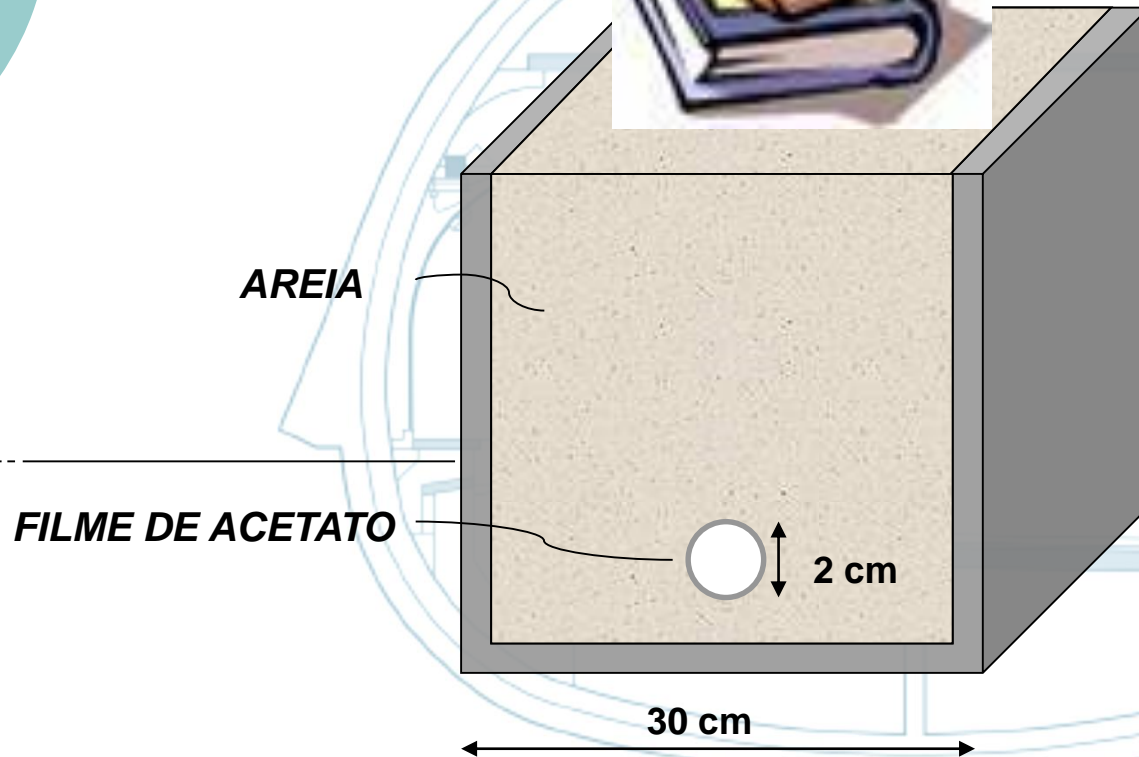
Recalques - Flexibilidade da Curva Yield-Density



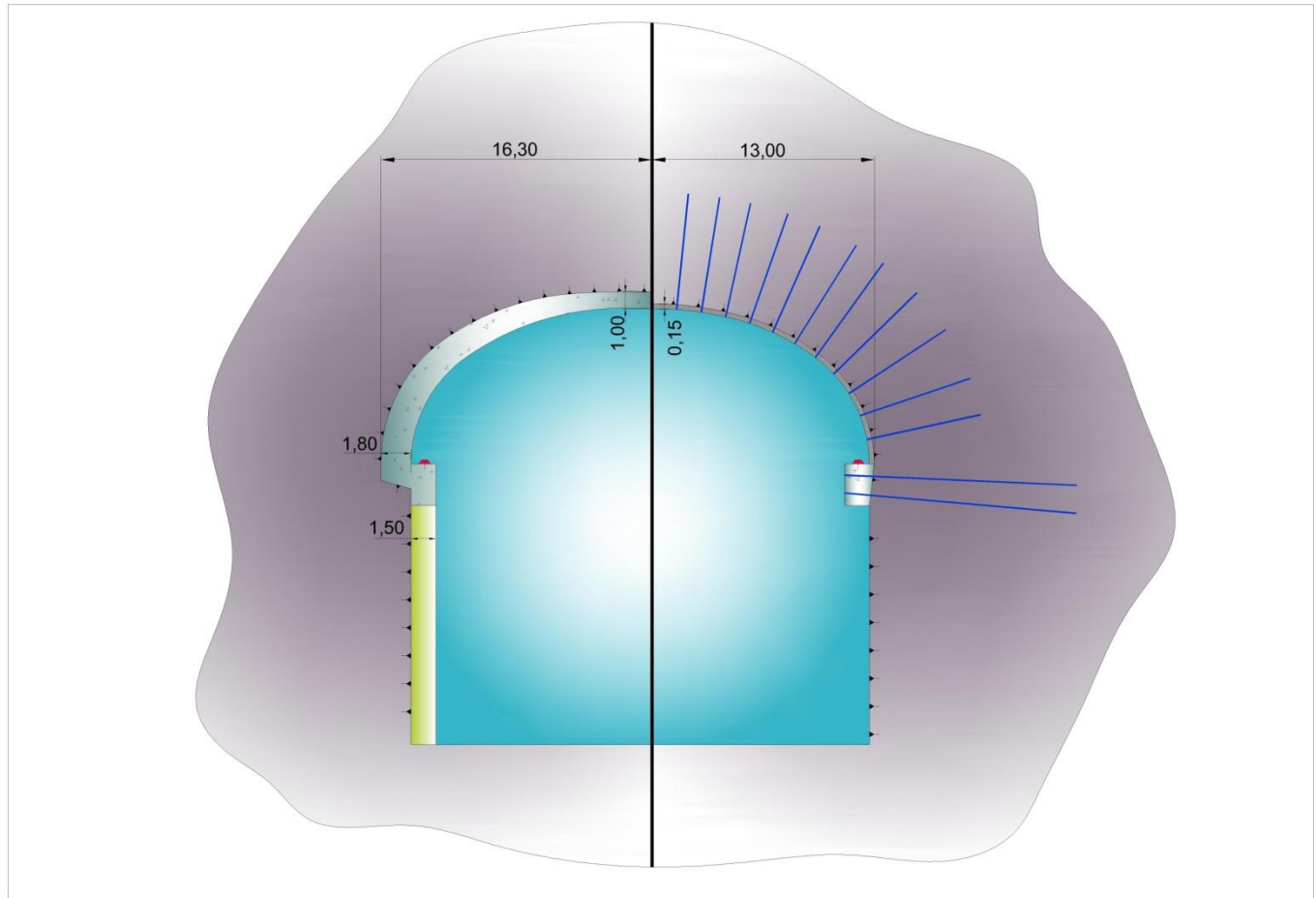
Túnel de Heathrow



Auto-sustentação de maciços



Caverna de Paulo Afonso IV



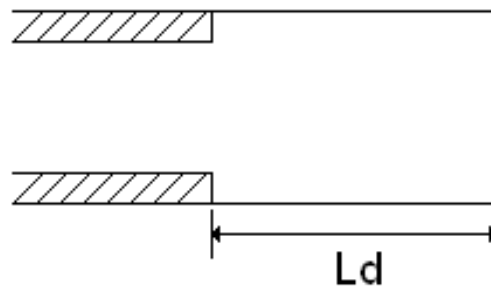
Projeto Estrangeiro

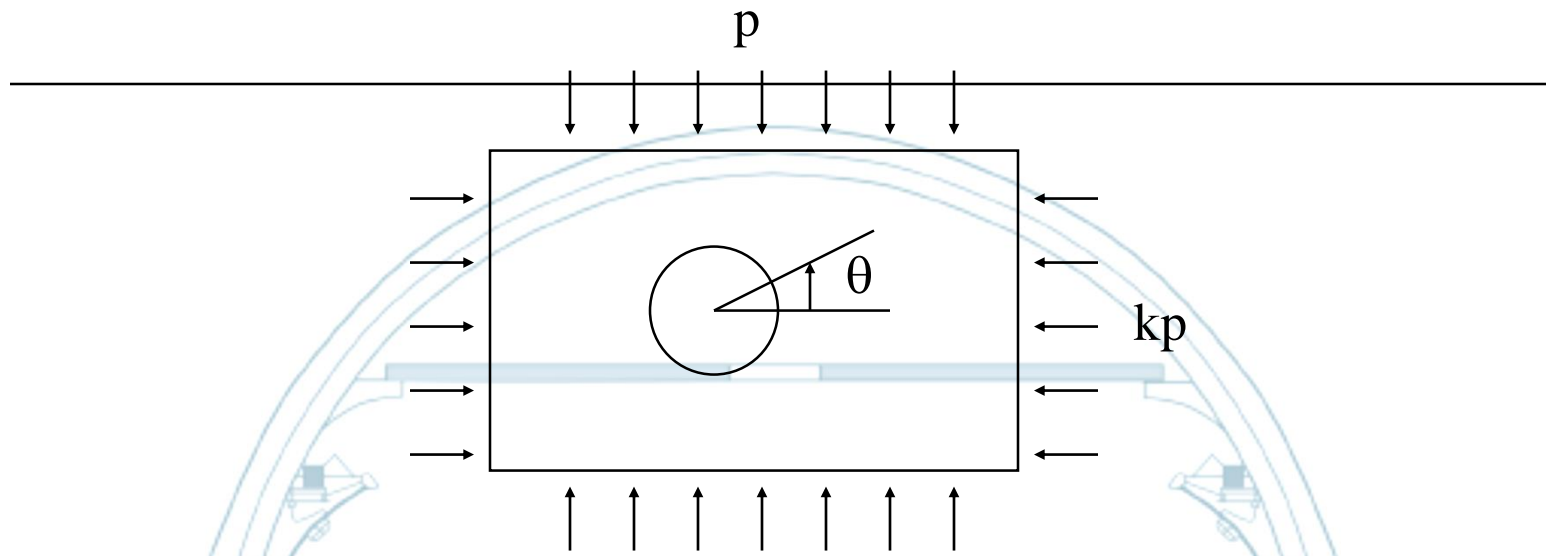
Projeto Brasileiro

Schwartz & Einstein (1980)

Método de convergência-confinamento

- 1 - T , M da interação maciço-suporte (Solução 2D)
- 2 - λ_d correção devida a atraso da instalação do suporte, L_d
- 3 – Plastificação do maciço





$$\frac{T}{pR} = \frac{1}{2}(1+k)(1-a_0^*) + \frac{1}{2}(1-k)(1-2a_2^*)\cos^2 \theta$$

$$\frac{M}{pR^2} = \frac{1}{2}(1-k)(1-2a_2^*)\cos 2\theta$$

$$\frac{uE}{pR(1+\nu)} = \frac{1}{2}(1+k)a_0^* - (1-k)\left[(5-6\nu)a_2^* + (1-\nu)\right]\cos 2\theta$$

$$a_0^* = \frac{C^* F^* (1-\nu)}{C^* + F^* + C^* F^* (1-\nu)} \quad C^* = \frac{ER(1-\nu_s^2)}{E_s A_s (1-\nu^2)}$$

$$a_2^* = \frac{(F^* + 6)(1-\nu)}{2F^*(1-\nu) + 6(5-6\nu)} \quad F^* = \frac{ER^3(1-\nu_s^2)}{E_s I_s (1-\nu^2)}$$

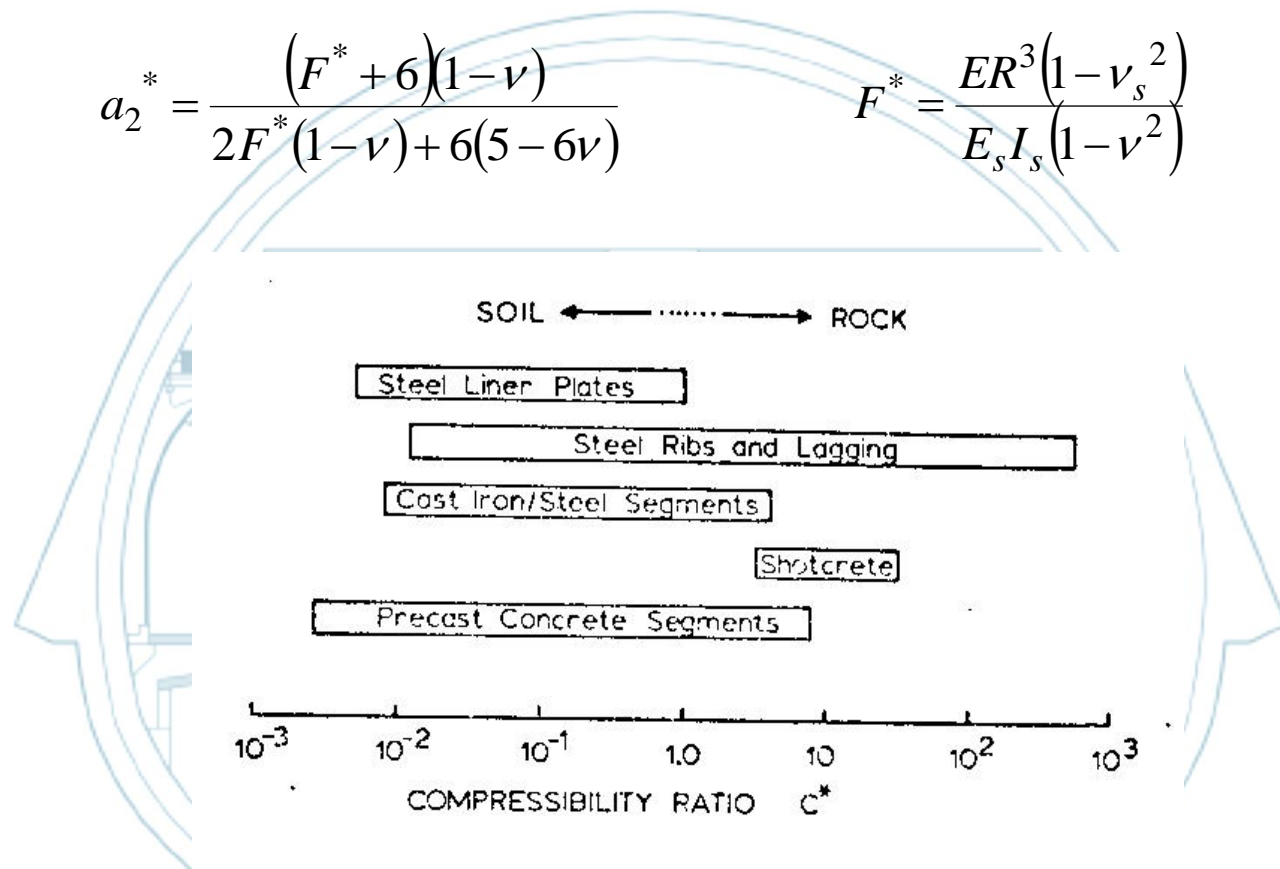
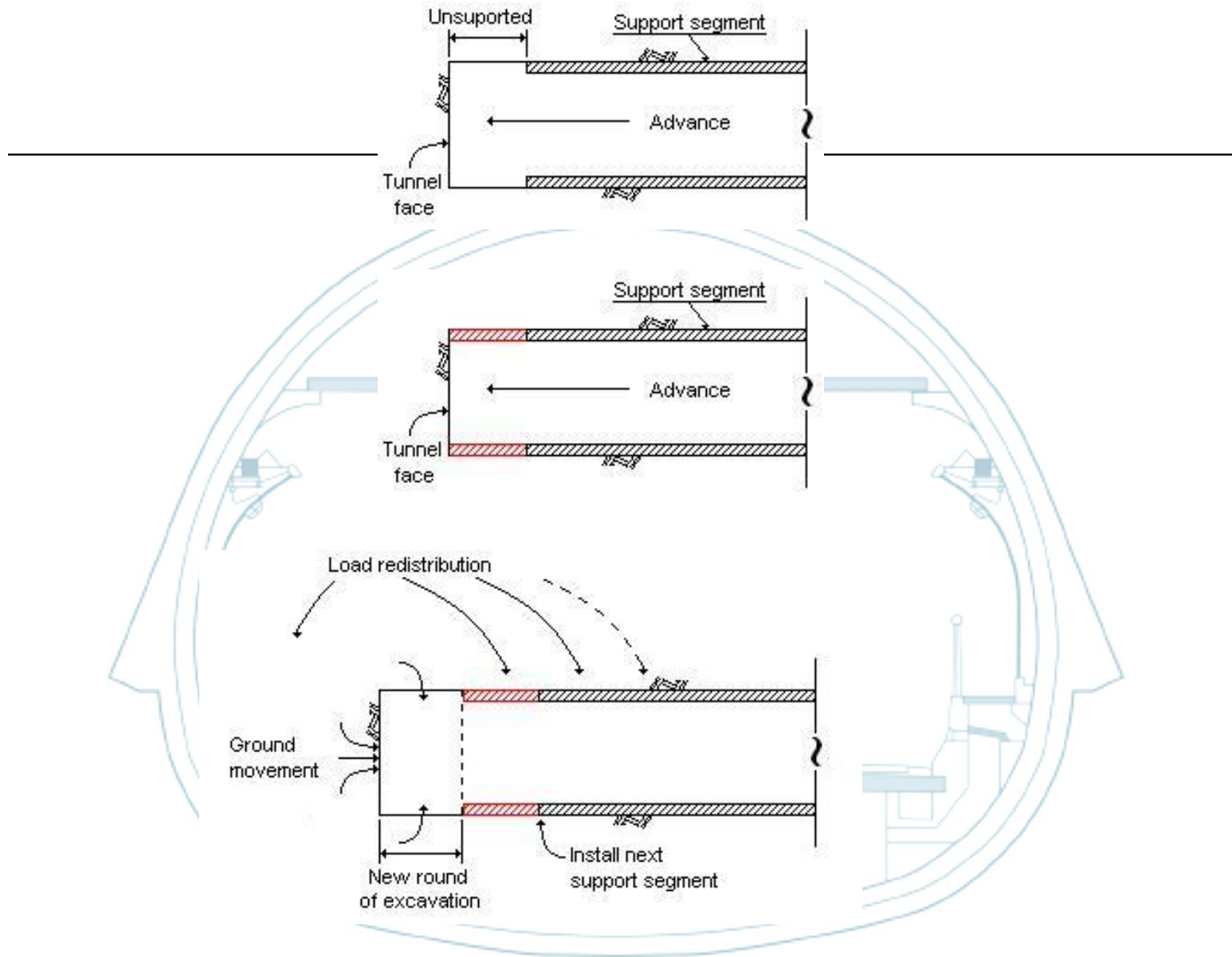


FIGURE 2.4. RANGES OF C* FOR COMMON SUPPORT SYSTEMS



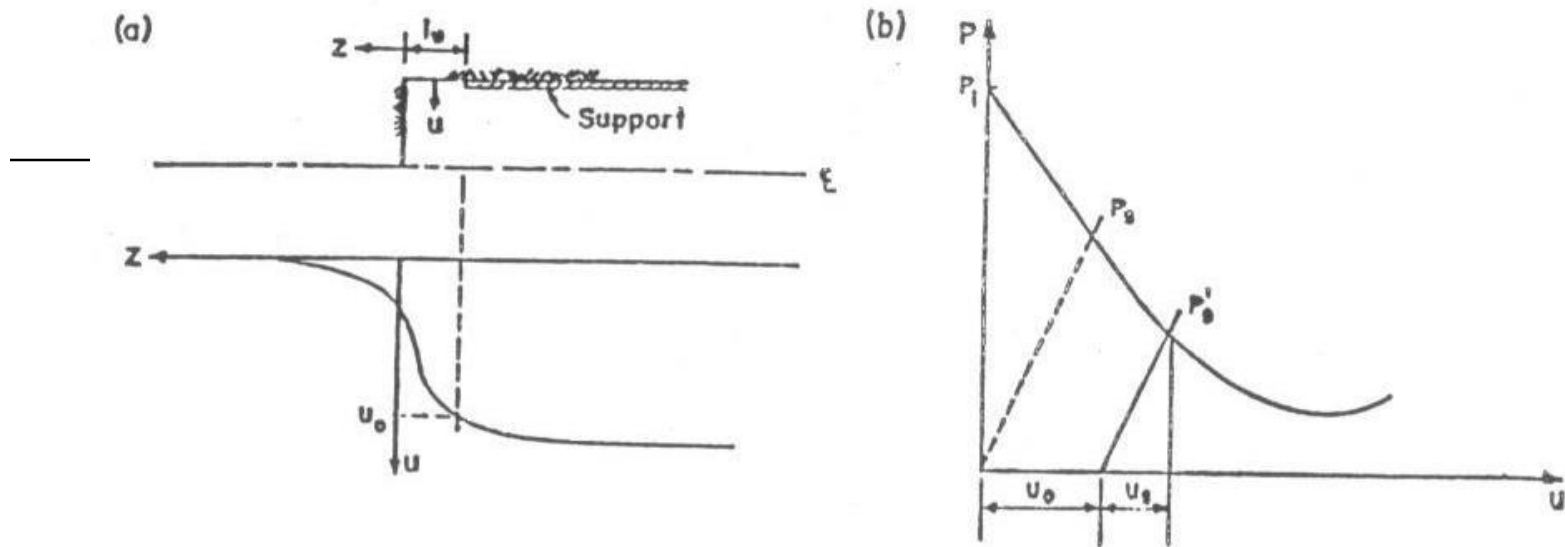


FIGURE 3.2 EFFECT OF SUPPORT DELAY ON SUPPORT LOADS

Case	Radius R	Ground Properties		Support Properties			C*	F*
		E	ν	E_g	ν_g	h		
1	10 ft.	15000 psi	0.30	1.94×10^6 pol	0.30	6.0 in.	0.134	484.0
2A	10	5000	0.40	1.94×10^6	0.30	6.0	0.0528	191.0
2B	10	5000	0.30	1.94×10^6	0.30	6.0	0.0447	161.0
3	10	1.5×10^5	0.15	3.0×10^6	0.15	6.0	1.0	4800
4	10	1.5×10^6	0.15	3.0×10^6	0.15	6.0	10.0	48000

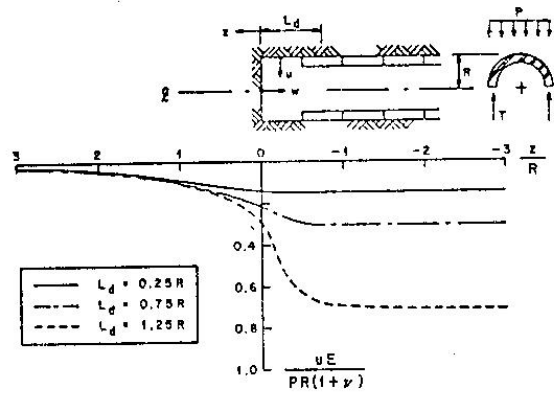


FIGURE 5.5. RESULTS FROM ELASTIC FINITE ELEMENT ANALYSES--
CASE 1 (SOFT GROUND)

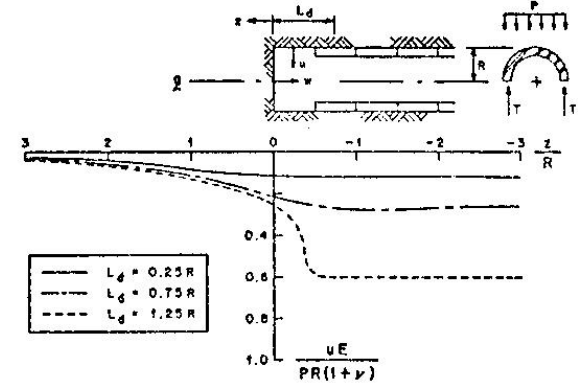
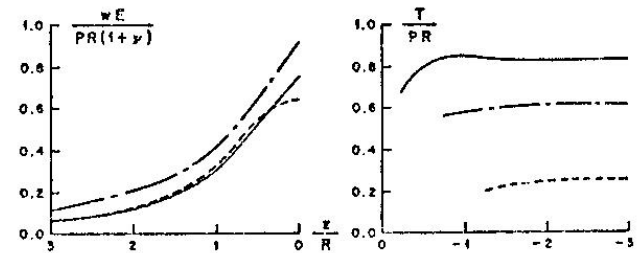
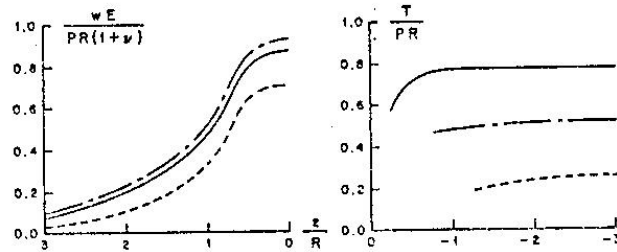


FIGURE 5.6. RESULTS FROM ELASTIC FINITE ELEMENT ANALYSES--
CASE 2A (SOFT GROUND)



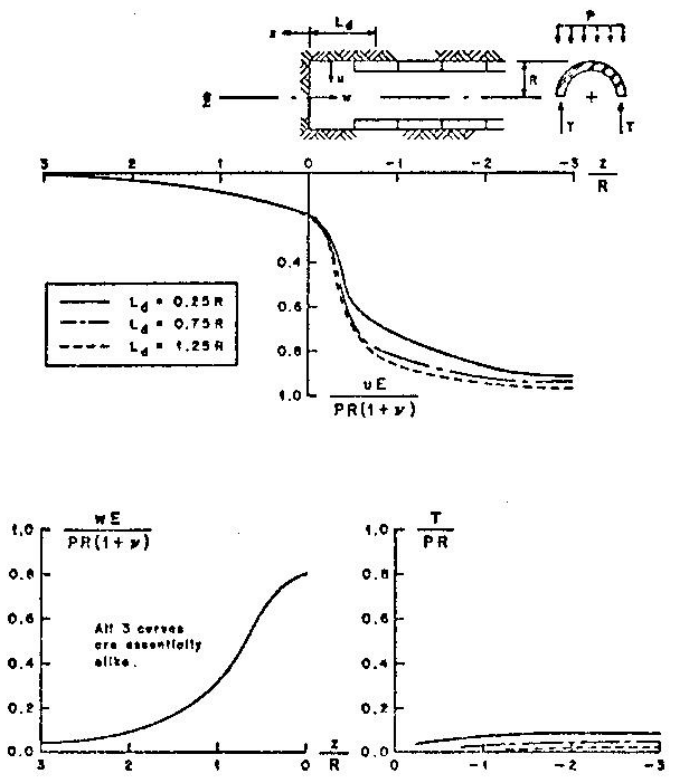


FIGURE 3.9. RESULTS FROM ELASTIC FINITE ELEMENT ANALYSES--
CASE 4 (ROCK)

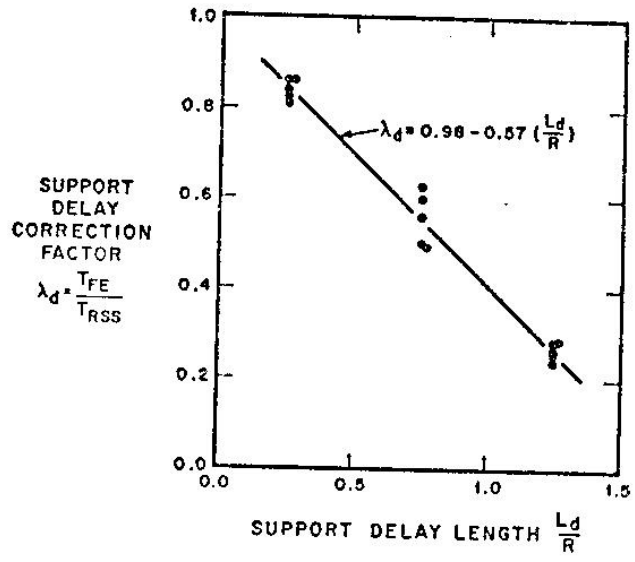


FIGURE 3.15. SUPPORT DELAY CORRECTION FACTOR

$$\lambda_d = \frac{T_{FE}}{T_{RSS}} = 0,98 - 0,57 \left(\frac{L_d}{R} \right)$$

Concreto projetado

Rigidez crescente com o tempo

- Modelo reológico complexo
- Deformação lenta
- Retração
- Ganho de rigidez com o tempo

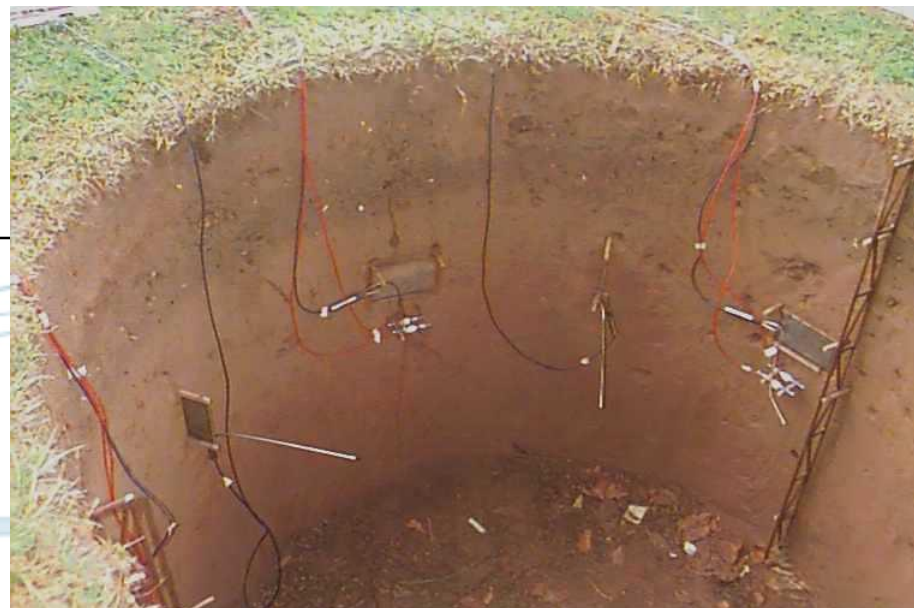
Pesquisa na EESC-USP sobre modelos estruturais de campo

Concretagem dos modelos



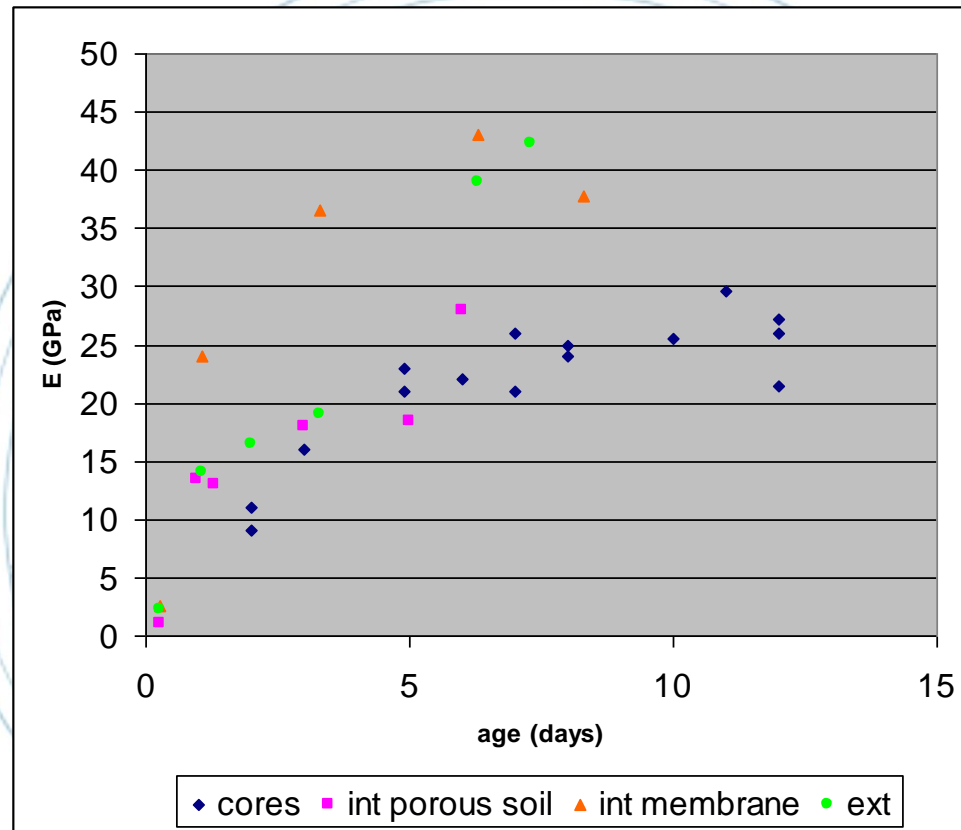
Aplicação do carregamento





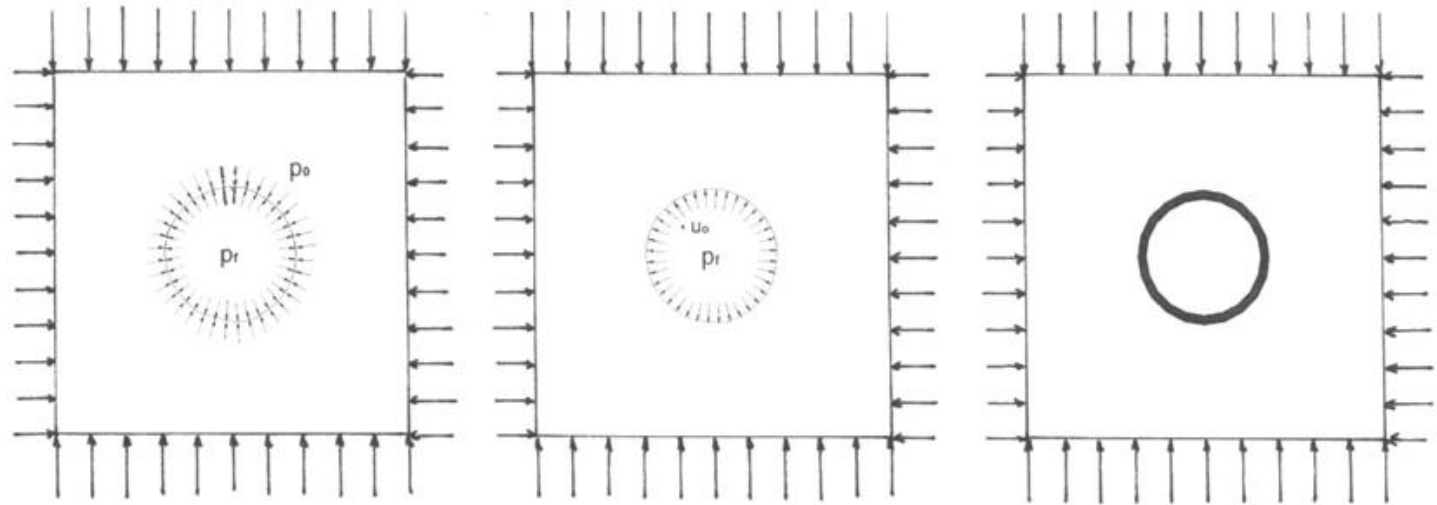
Modelo Estrutural II - Execução

E vs idade



Shotcrete for Underground Support

Análise 2D: Método da Pressão Fictícia (Panet, 1976)



$$p_r = p_0$$

Tensão inicial atuando no perímetro a ser escavado

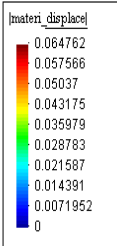
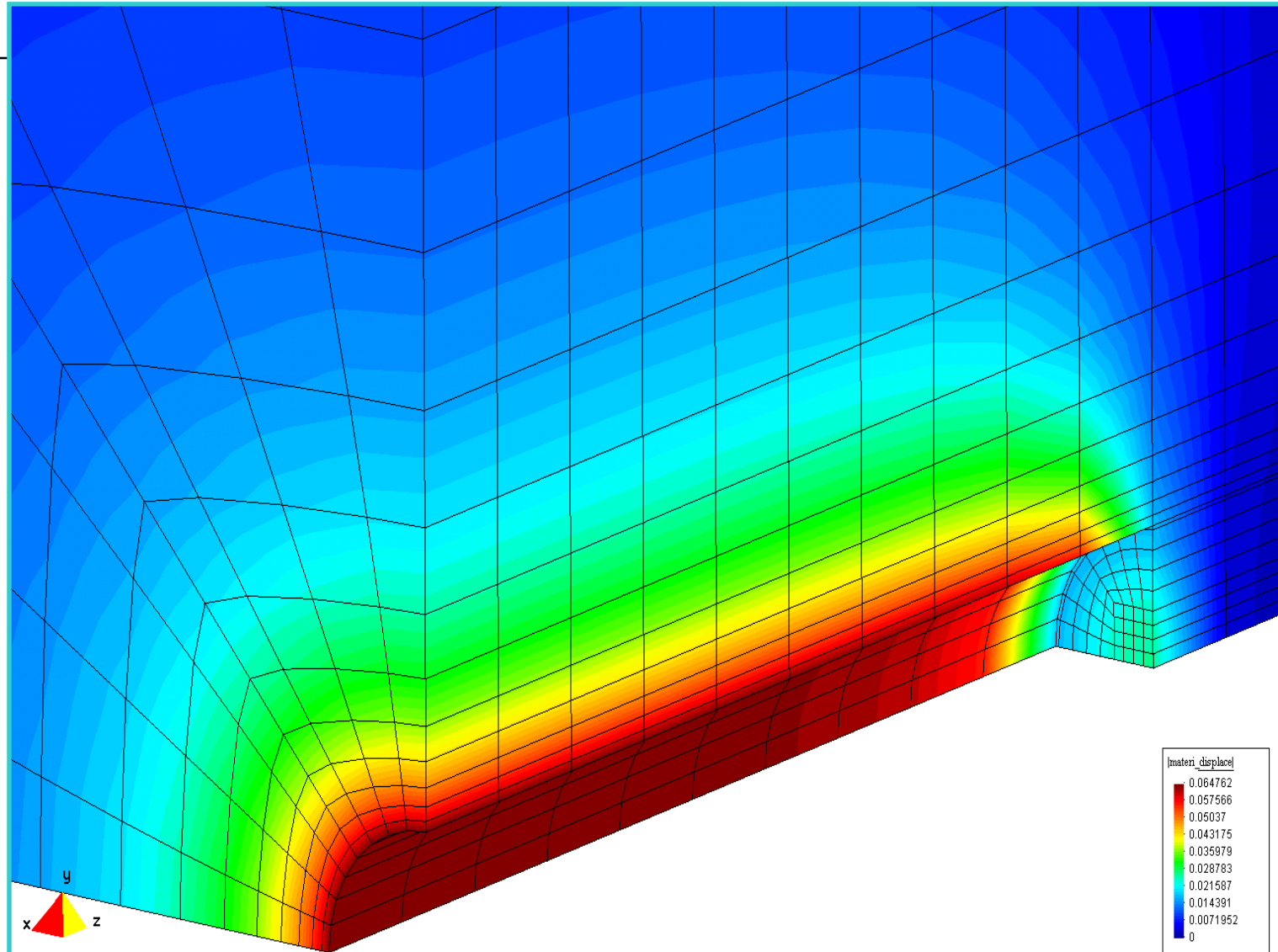
$$p_r = \alpha \cdot p_0$$

Escavação, aplicação de pressão fictícia no perímetro

$$p_r = \text{zero}$$

Instalação do suporte e eliminação da pressão fictícia

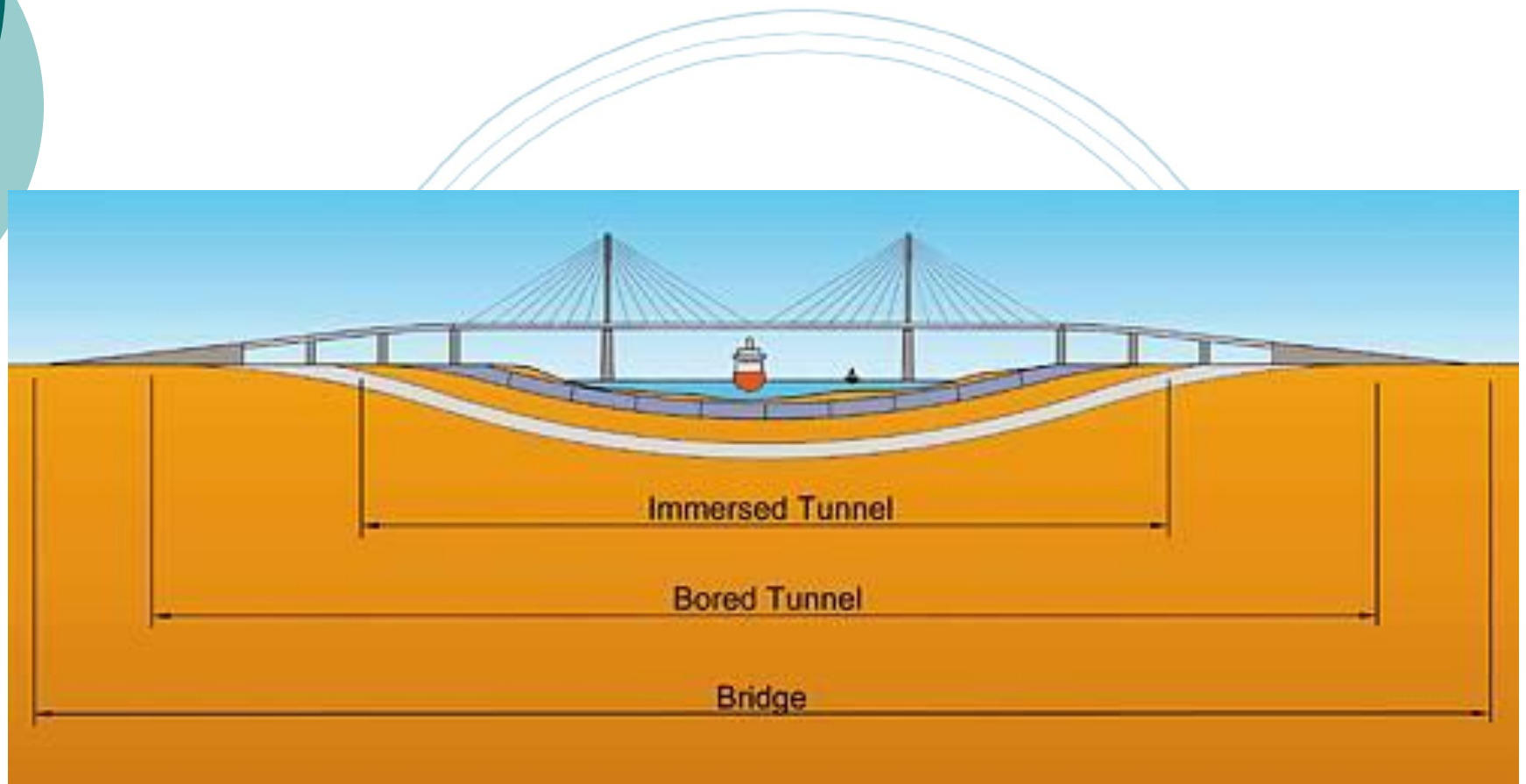
Métodos Rigorosos - Análise 3-D na região da frente de escavação



6 - Túnel Imerso Santos-Guarujá



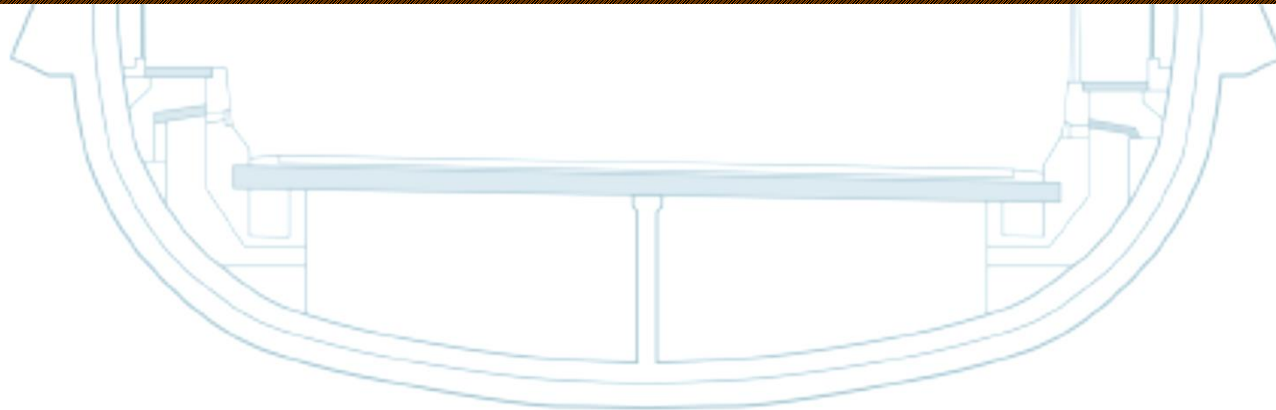
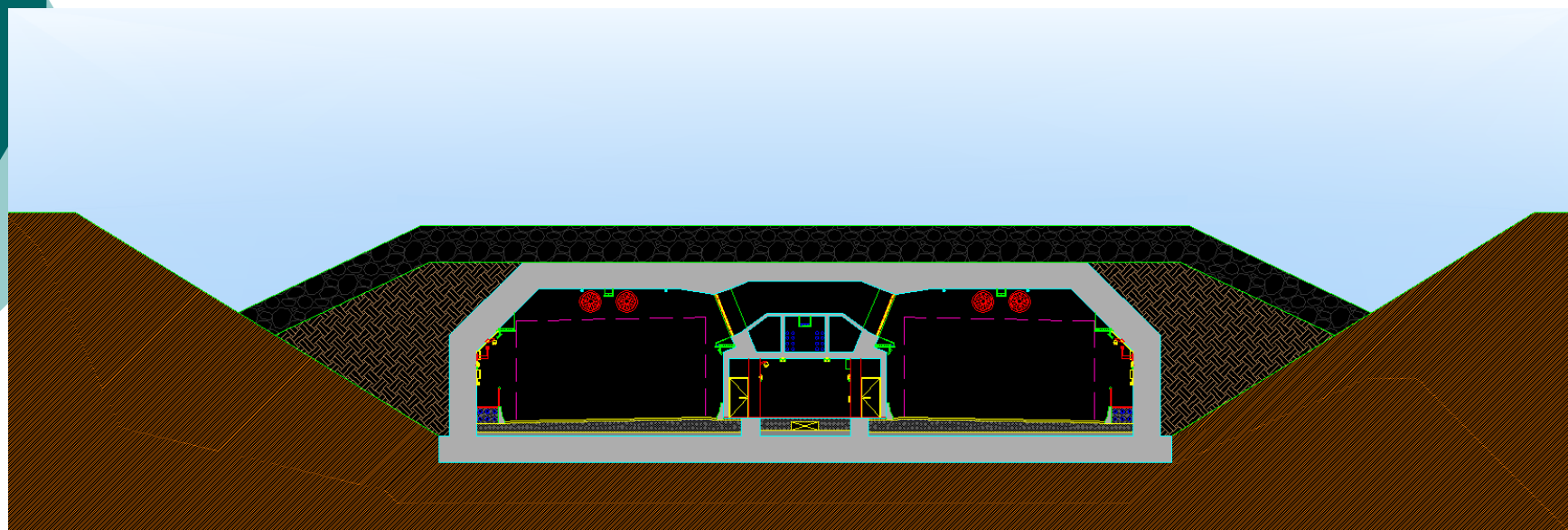
Pontes e Túneis



IMPLANTAÇÃO TÚNEL SUBMERSO SANTOS - GUARUJÁ



SEÇÃO TRANSVERSAL TÚNEL SUBMERSO SANTOS - GUARUJÁ

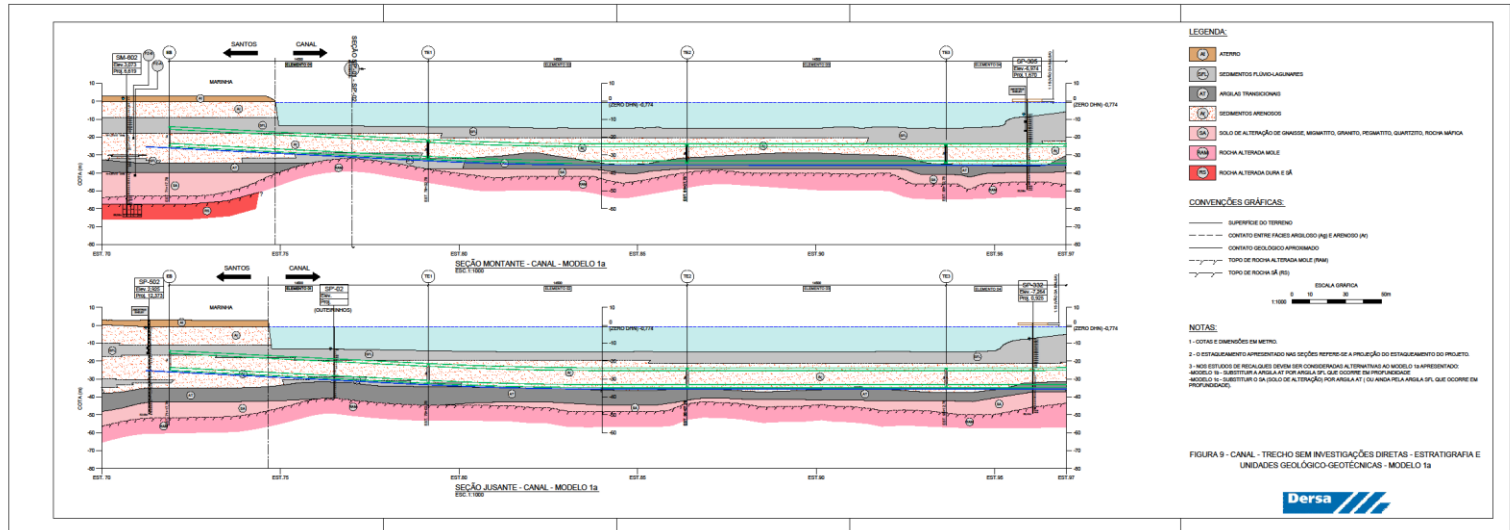


Cone Penetration Test





Seção Geológica

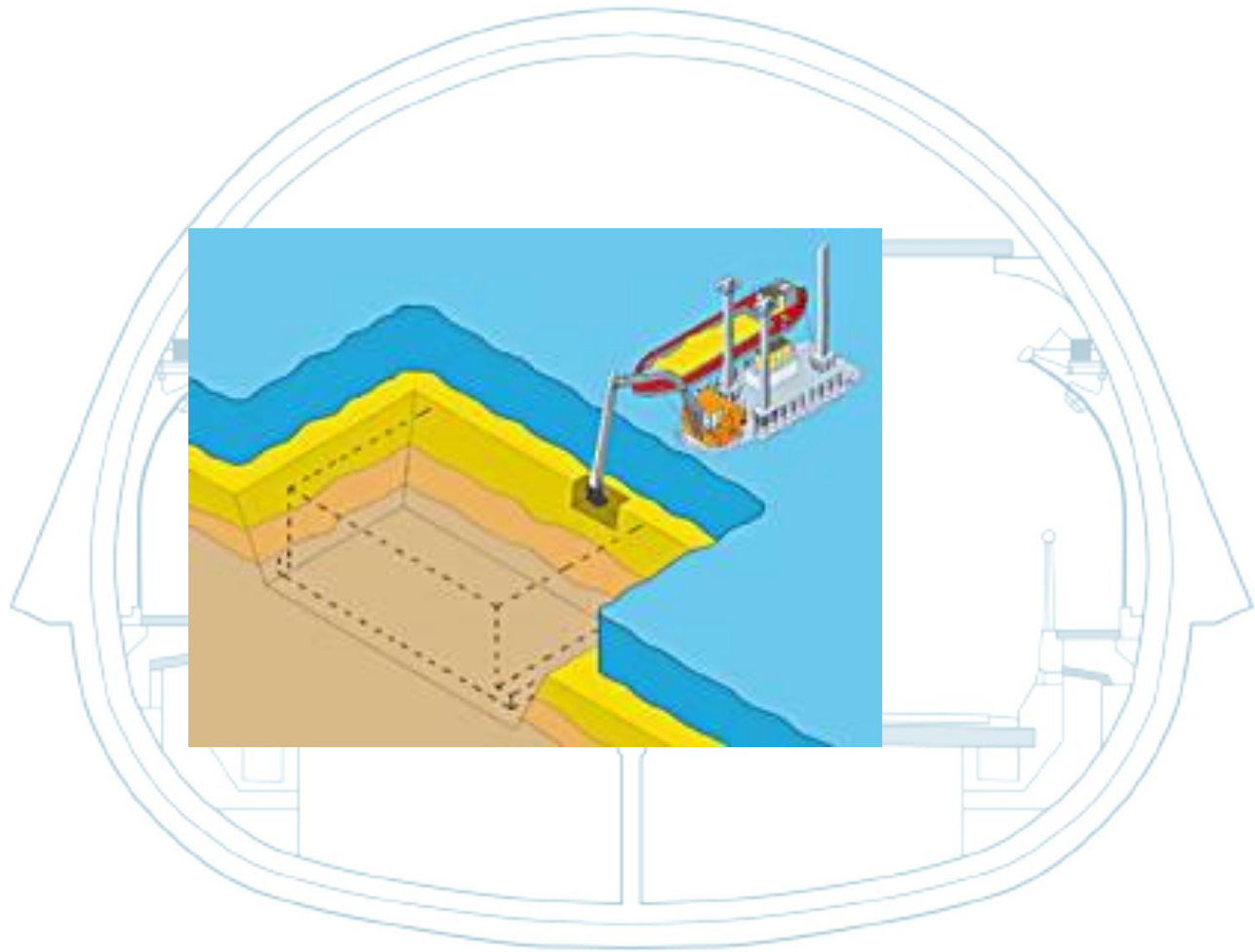




Oresund

Processo Construtivo

1 – Dragagem do leito



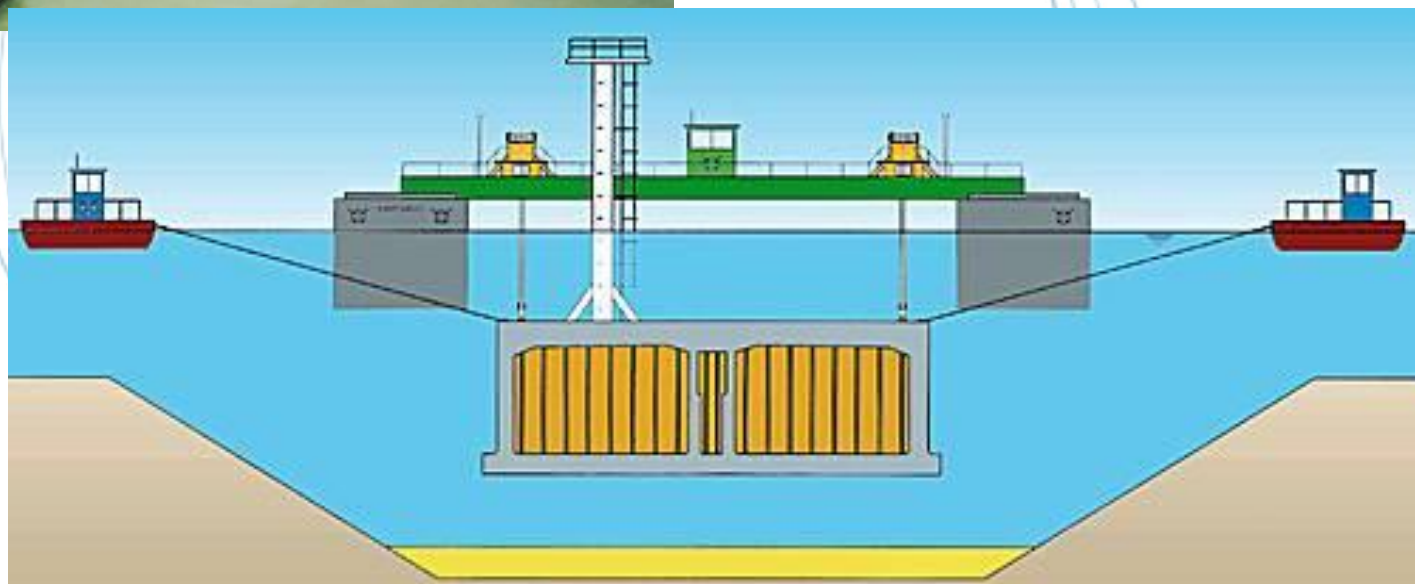
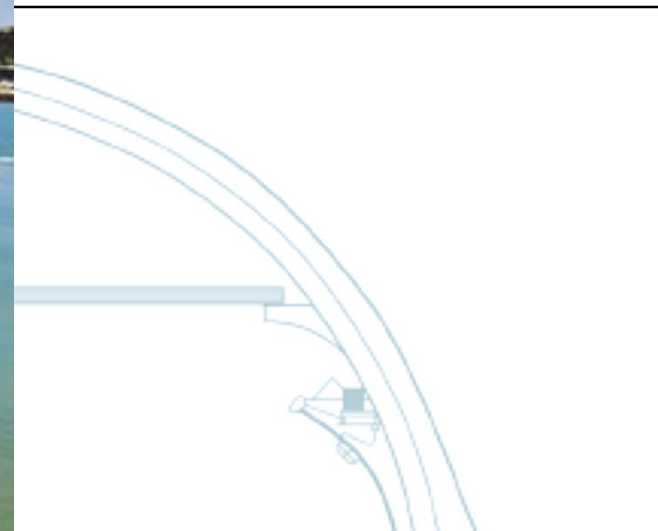
2 – Construção em paralelo de elementos pré-moldados



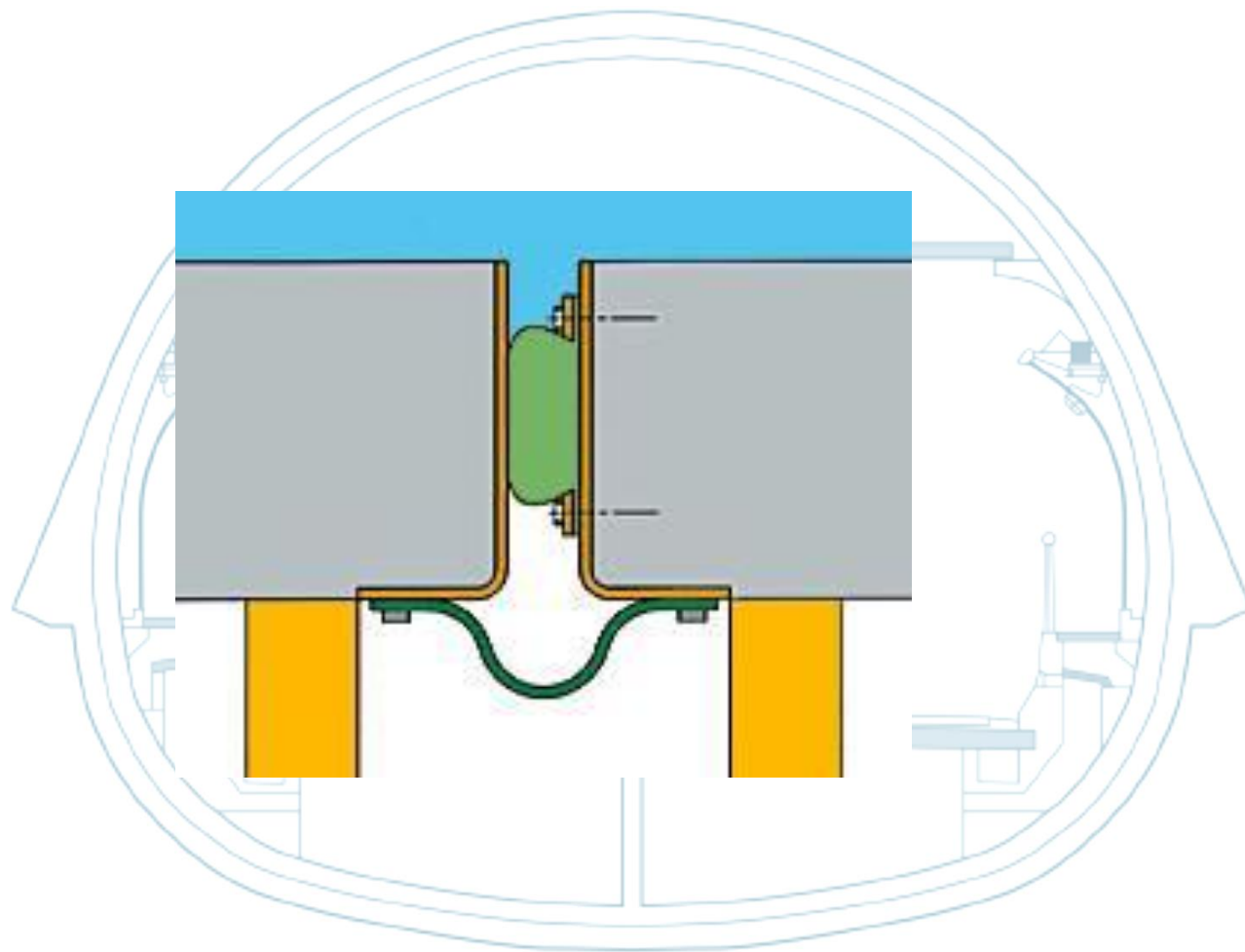
3 – Transporte de elementos pré-moldados



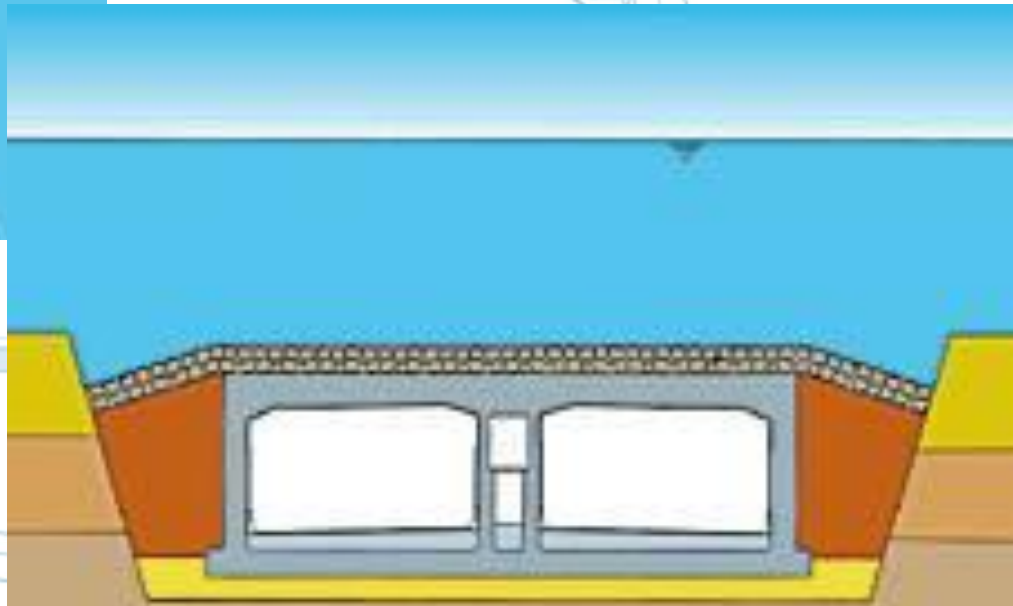
4 - Posicionamento



5 - Vedação

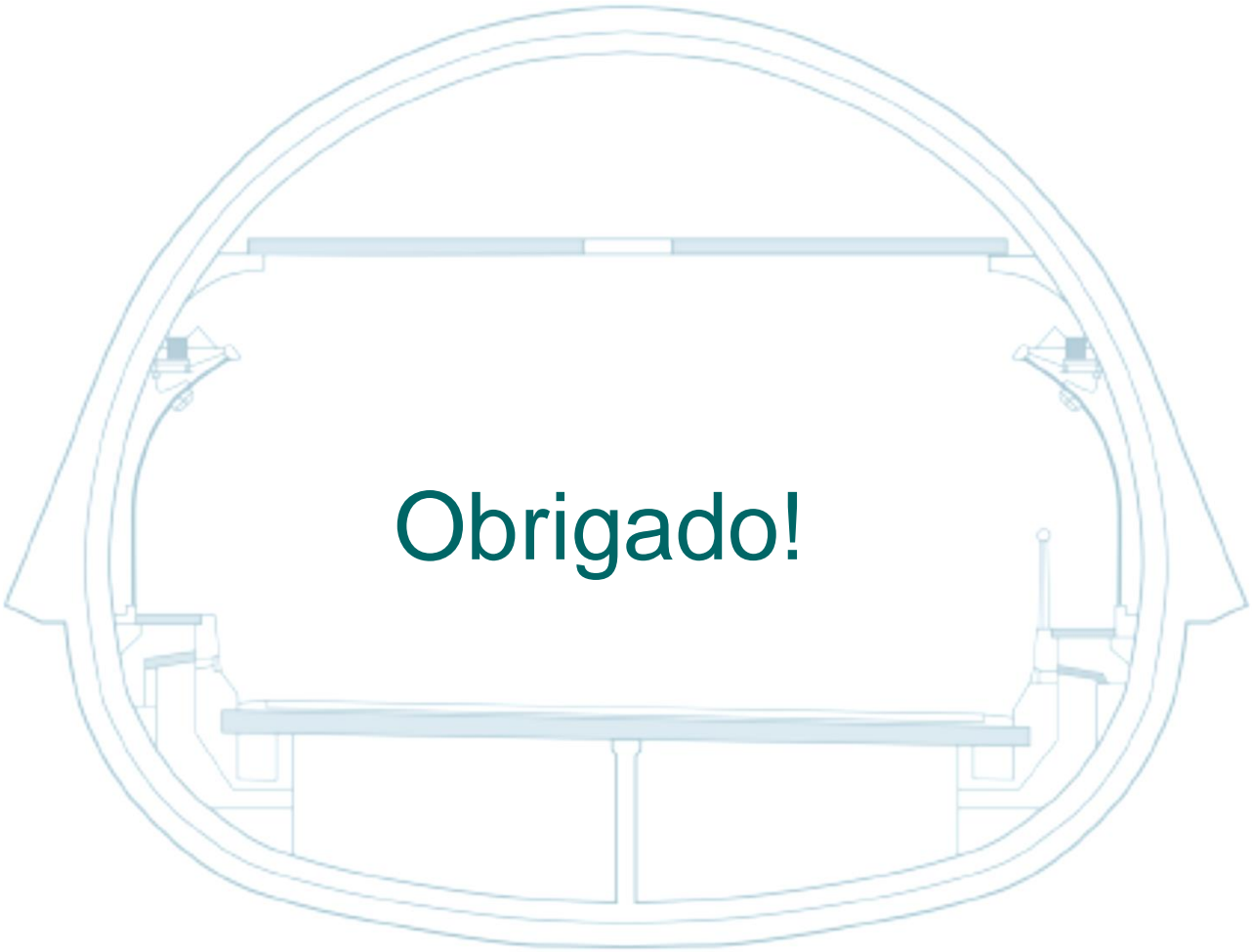


Reaterro



Infraestrutura brasileira

- 118a no mundo (Fórum Econômico Mundial)
- Safra de grãos: caminhões atolados
- Comunidade Europeia: 1,5 tri € até 2030
- Índia: Metrô Nova Delhi 45 km subterrâneo em construção com 35 máquinas ao tempo; 12 km de rodovia de 2 pistas por dia; Mumbai 17 máquinas ao mesmo tempo
- Cingapura: 57 TBMs ao mesmo tempo



Obrigado!