DIFFERENTIAL WEATHERING AND ADVERSE DISCONTINUITIES WERE THE APPARENT CAUSES OF A TRAGIC METRO ACCIDENT IN BRAZIL

Dr. N. R. Barton, Nick Barton & Associates, Oslo

FF marks eastern boundary of collapse– a steep discontinuity beneath Rua Capri

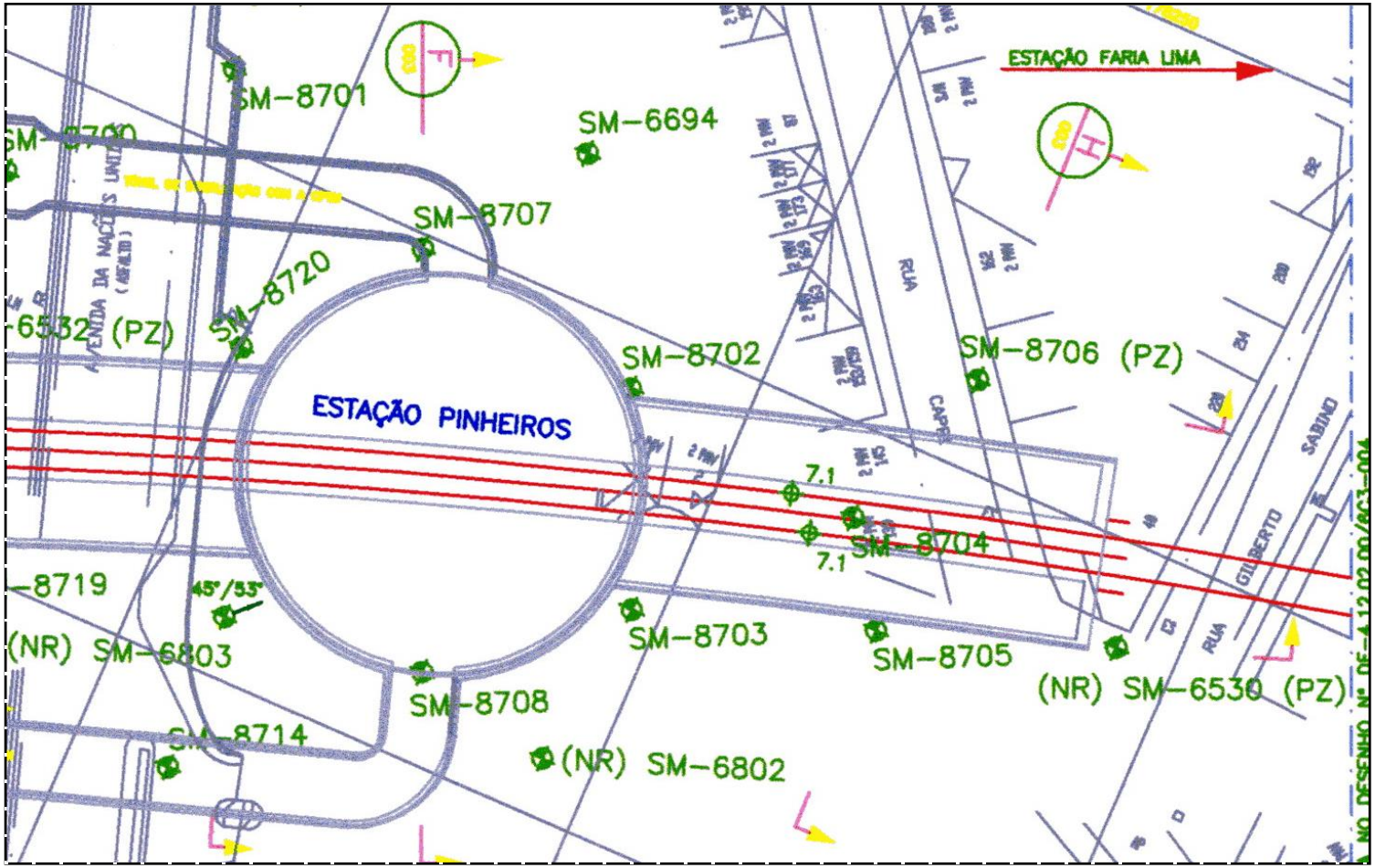
Location next to 7 traffic lanes and railway.

(Noise problem for 1997 refraction seismic by IPT, no V_P)

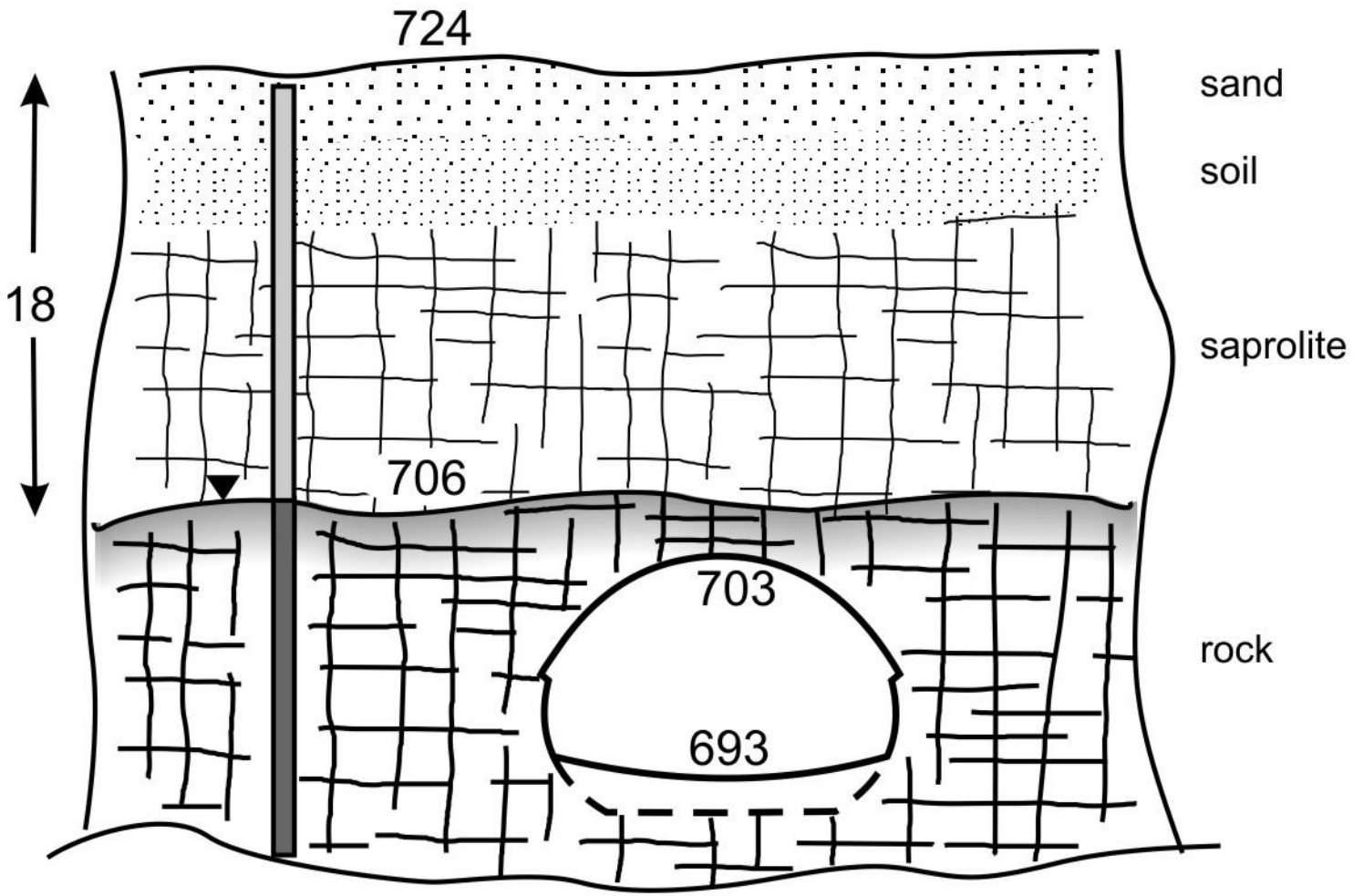
Eleven boreholes around shaft and eastern station cavern.

Exceeds international norm:

L borehole / L tunnel .....by a factor of ≈ 2 to 4.



WHAT WAS EXPECTED – *ON AVERAGE* – CONCERNING ROCK COVER



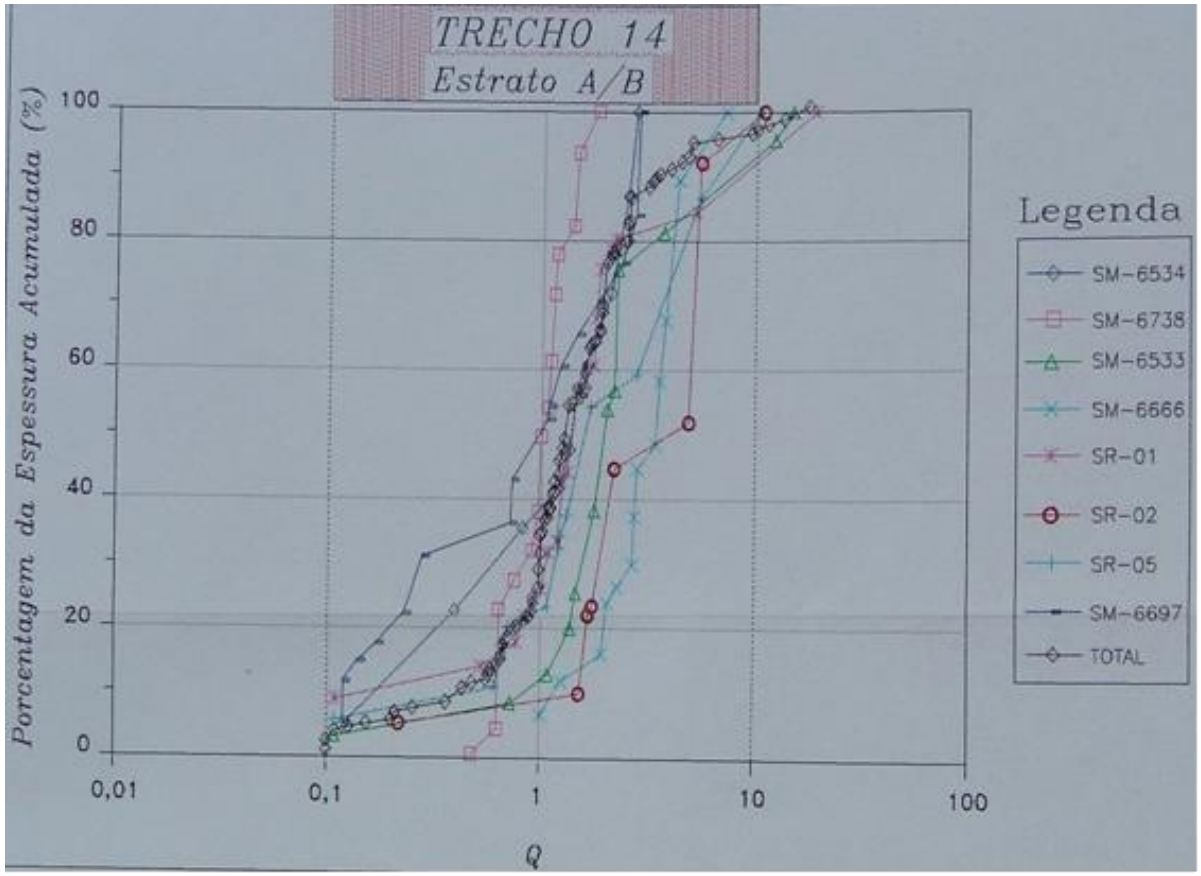
Borehole SM-8704 drilled near centre of (future) station cavern.

Rock encountered at 18 m depth, at elevation 706m.
(3 m above cavern roof)

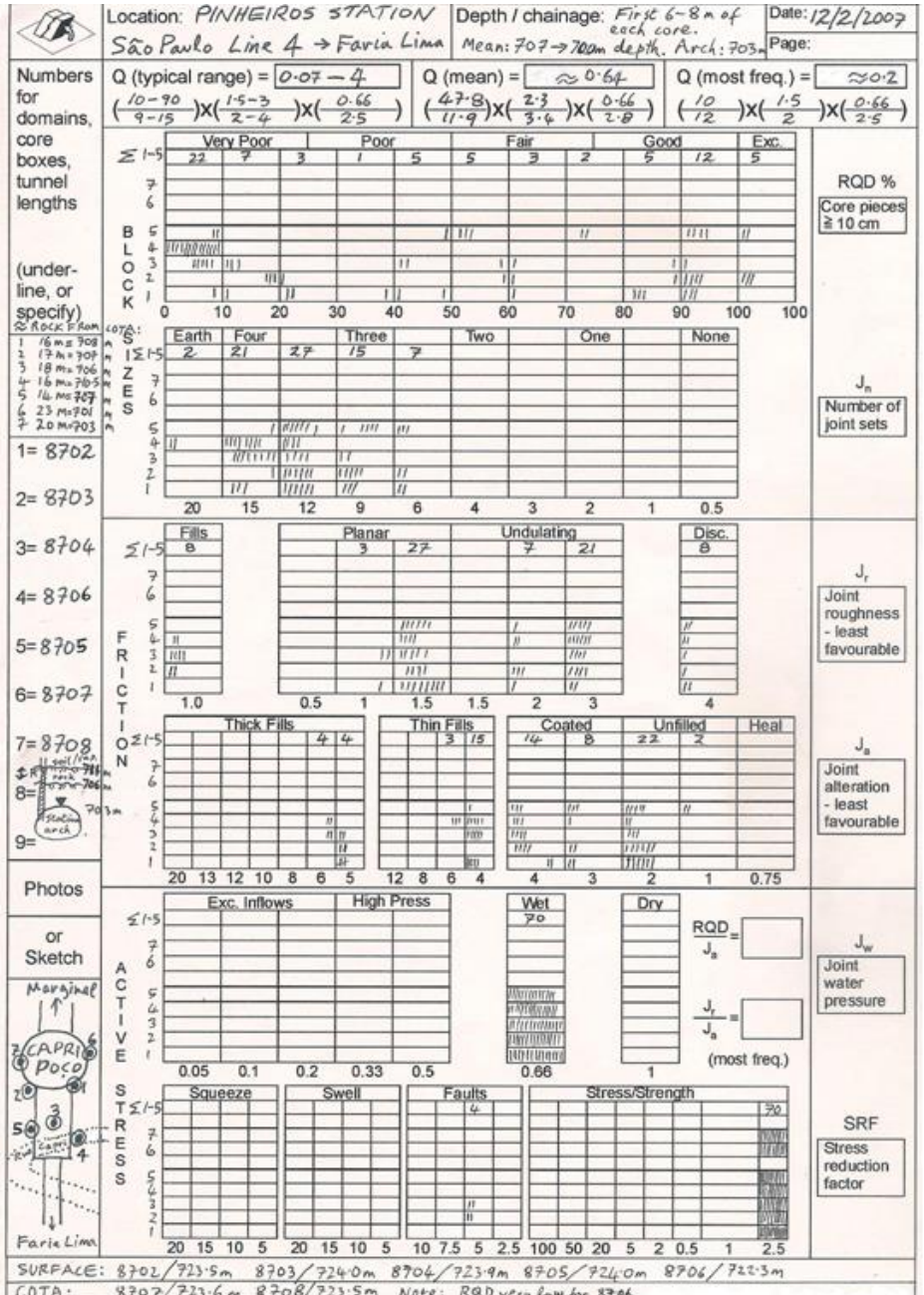
Low rock cover 'confirmed' – same as mean of five holes nearest cavern (see next two holes also!)

Note consistent
17 to 18 m
of soil and saprolite
in closest boreholes
8702 and 8703

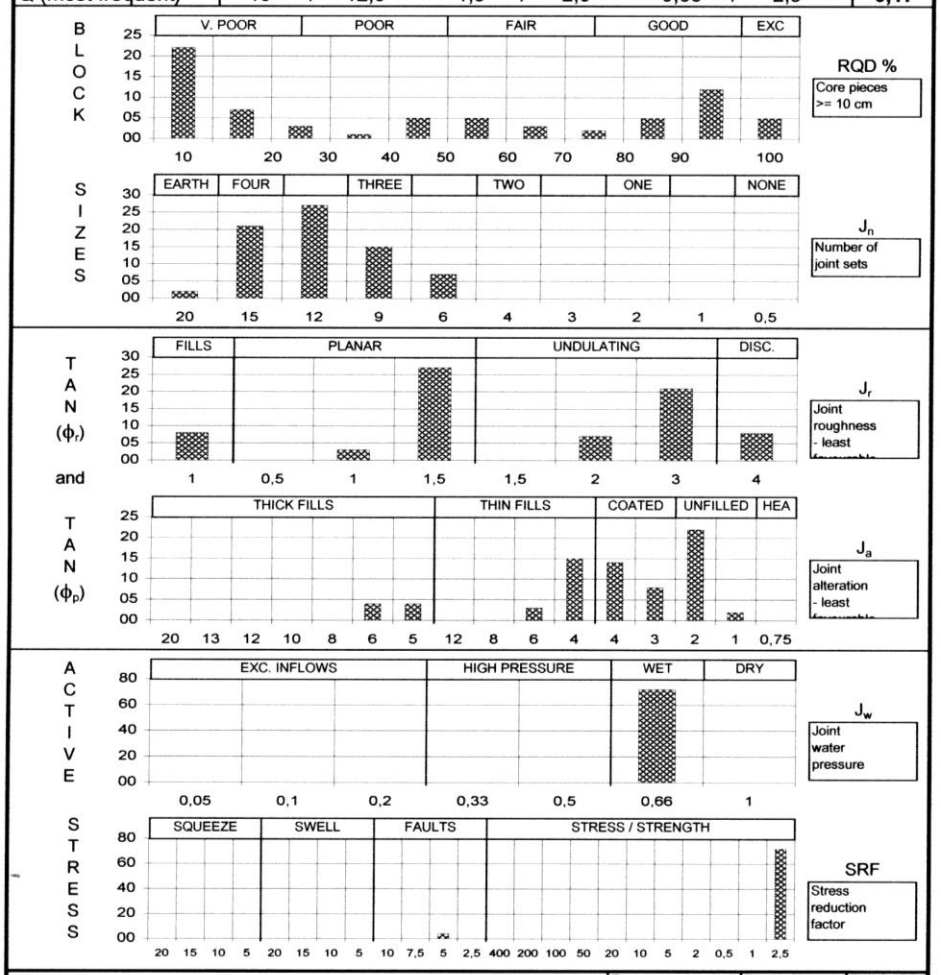
Most of the Q-logging performed in 1996-7 (this figure).....was comparable to the post-collapse Q-logging (by NB) of the nearest holes, drilled by CVA



Post-collapse Q-logging of 5 nearest borehole cores



Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	15,0	*	1,5	/	4,0	*	0,66	/	2,5	=	**0,066**
Q (typical max)=	90	/	9,0	*	3,0	/	2,0	*	0,66	/	2,5	=	**4,0**
Q (mean value)=	48	/	11,9	*	2,2	/	3,4	*	0,66	/	2,6	=	**0,63**
Q (most frequent)=	10	/	12,0	*	1,5	/	2,0	*	0,66	/	2,5	=	**0,17**



PINHEIROS STATION CAVERN COLLAPSE

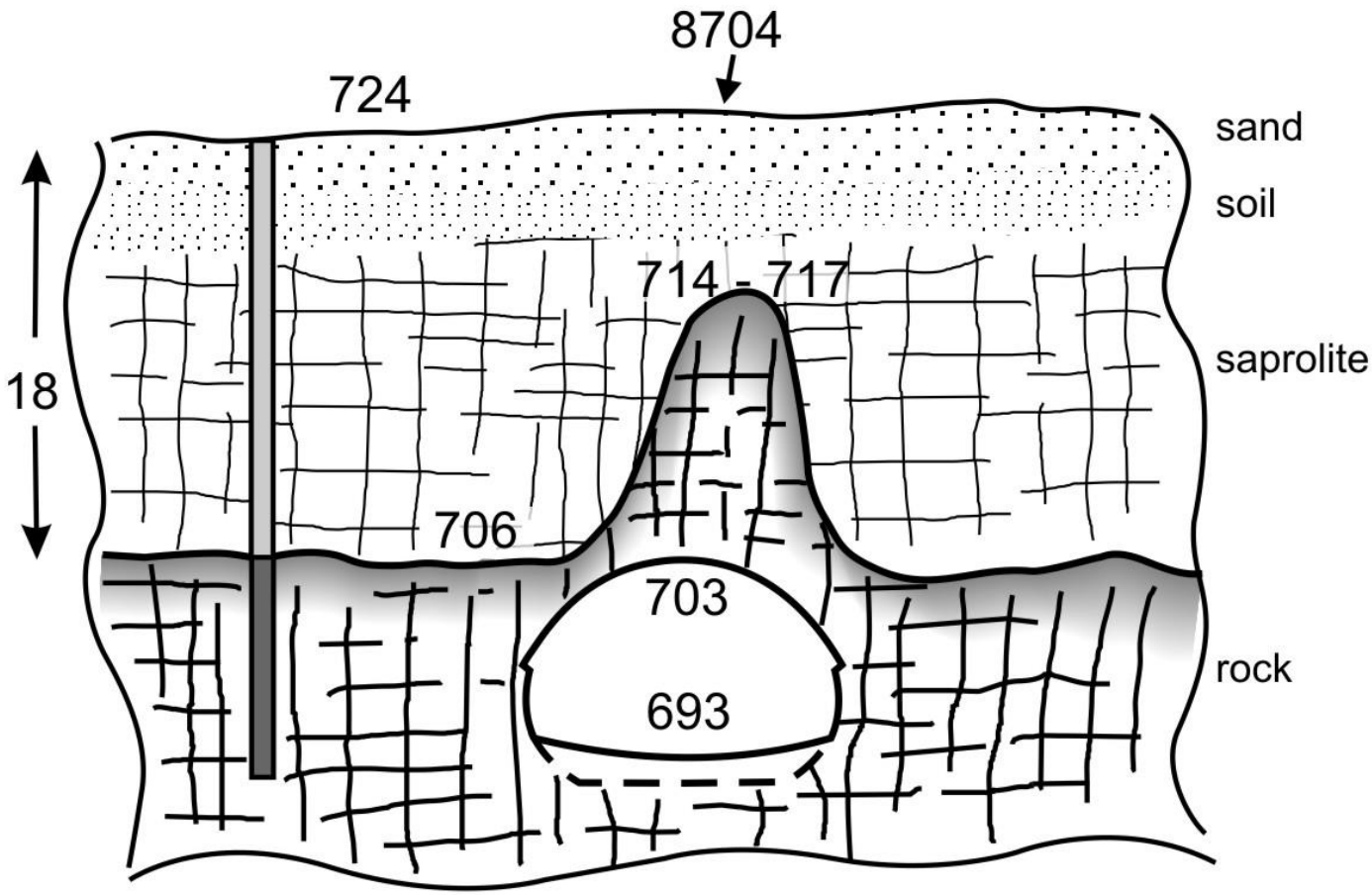
Q-histogram logging of top 8 m of core relevant to arch conditions, for closest 5 boreholes: 8702, 8703, 8704, 8705, and 8706. Top of rock at 16, 17, 18, 16, 14 meters.

Rev.	Report No.	Figure No.
Borehole No.: See left	Drawn by NB&A	Date 12.02.07
Depth zone (m) 22-26m	Checked nrb	
	Approved	

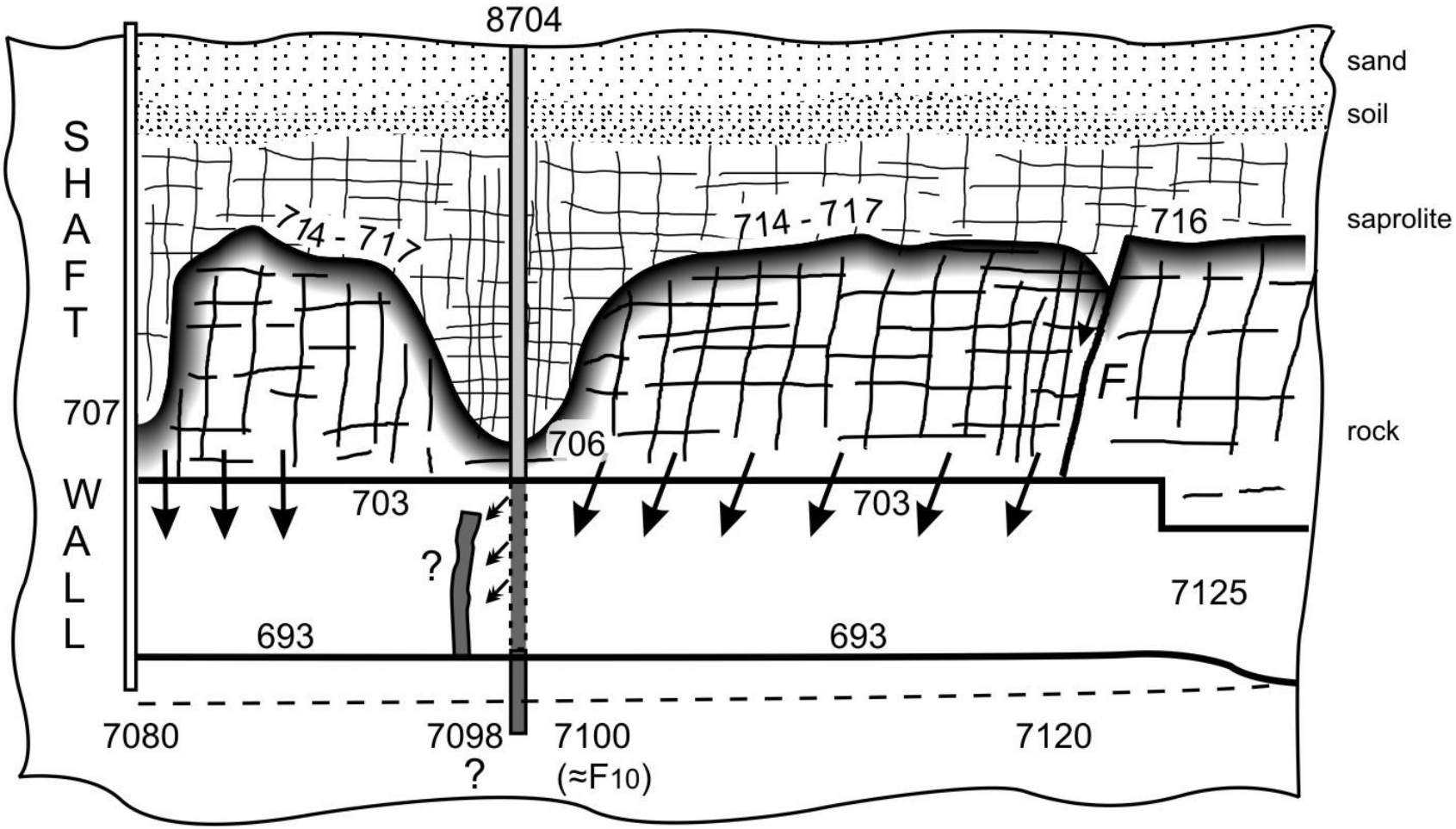
A microcosm of the jointing – long axis of cavern // to this text

EXTRAORDINARY REALITY: SUB-SURFACE RIDGE-OF-ROCK WENT UNDETECTED (grossly simplified here)

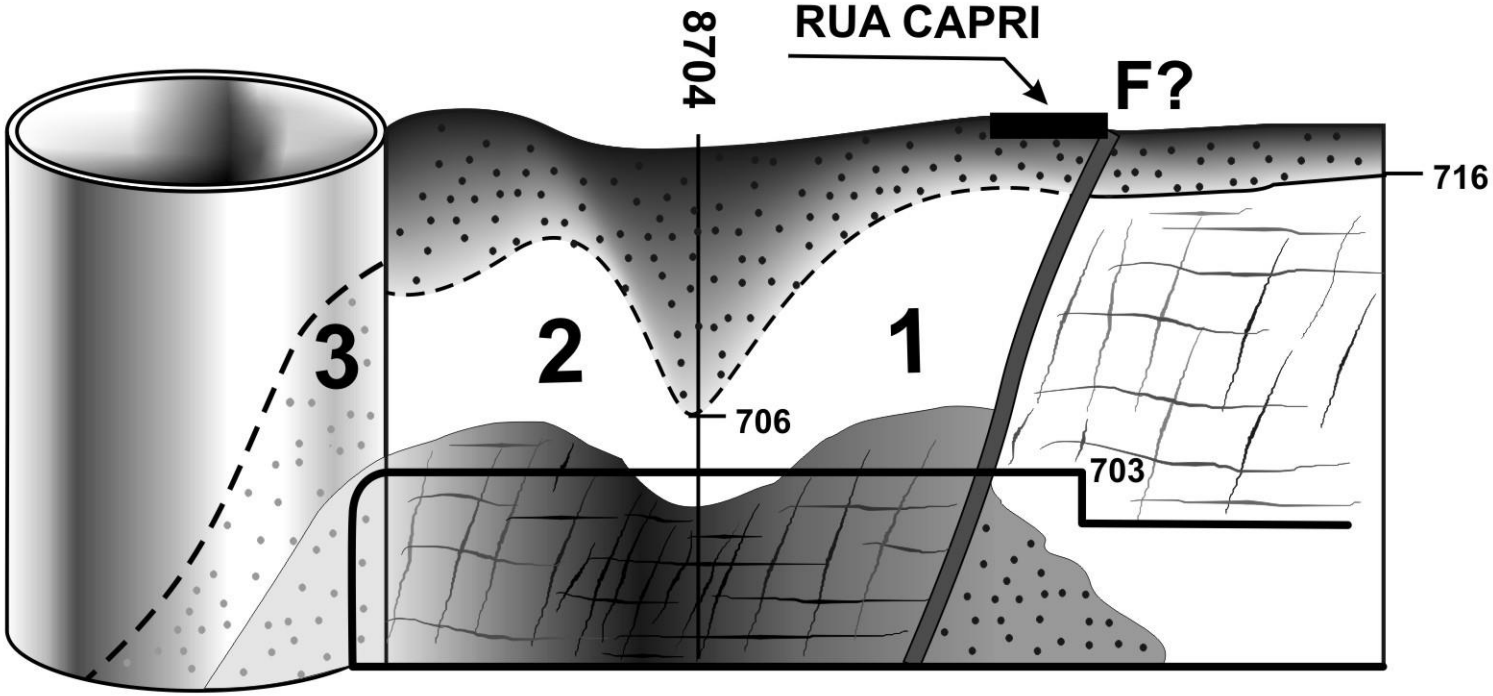
Most of collapsed rock in centre of cavern fell 8 to 10 m, reaching elevation 704-707 m, i.e. 1 to 4m above the (original) cavern arch.



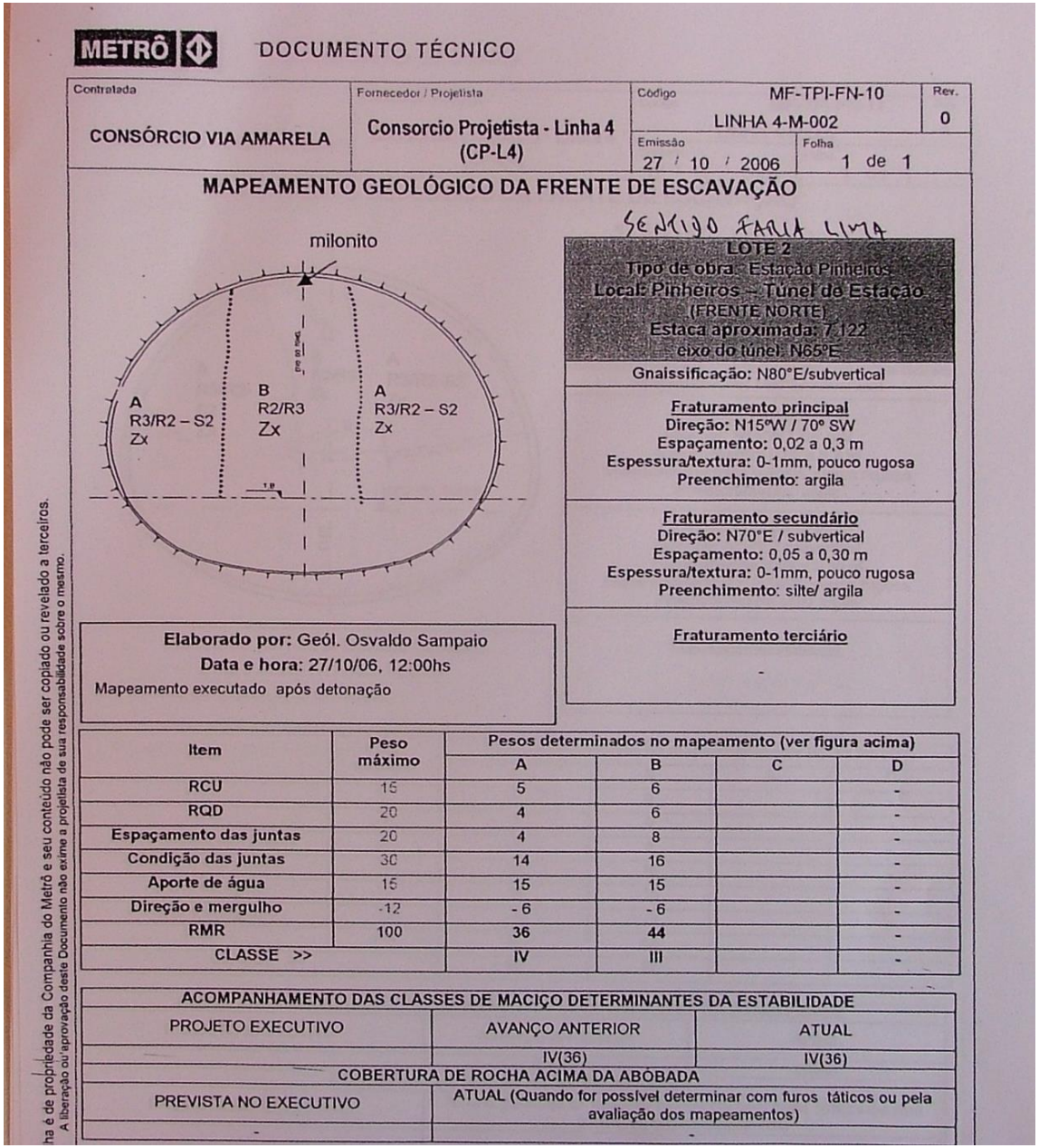
SCHEMATIC OF WHY RIDGE-of-ROCK WAS MISSED WHEN DRILLING



Principal components of the collapse



View of cavern floor after 15 months of post-collapse excavation



METRÔ DOCUMENTO TÉCNICO

Contratada	Fornecedor / Projetista	Código	Rev.
CONSÓRCIO VIA AMARELA	Consorcio Projetista - Linha 4 (CP-L4)	MF-TPI-FN-10 LINHA 4-M-002	0
		Emissão 27 / 10 / 2006	Folha 1 de 1

MAPEAMENTO GEOLÓGICO DA FRENTE DE ESCAVAÇÃO

SERGIO FARIA LIMA

milonito

A R3/R2 – S2 Zx

B R2/R3 Zx

A R3/R2 – S2 Zx

LOTE 2
Tipo de obra: Estação Pinheiros
Local: Pinheiros – Túnel de Estação (FRENTE NORTE)
Estaca aproximada: 7.122
eixo do túnel: N65ºE

Gnaissificação: N80°E/subvertical

Fraturamento principal
Direção: N15ºW / 70º SW
Espaçamento: 0,02 a 0,3 m
Espessura/textura: 0-1mm, pouco rugosa
Preenchimento: argila

Fraturamento secundário
Direção: N70°E / subvertical
Espaçamento: 0,05 a 0,30 m
Espessura/textura: 0-1mm, pouco rugosa
Preenchimento: silte/ argila

Fraturamento terciário
-

Elaborado por: Geól. Osvaldo Sampaio
Data e hora: 27/10/06, 12:00hs
Mapeamento executado após detonação

Item	Peso máximo	Pesos determinados no mapeamento (ver figura acima)			
		A	B	C	D
RCU	15	5	6		-
RQD	20	4	6		-
Espaçamento das juntas	20	4	8		-
Condição das juntas	30	14	16		-
Aporte de água	15	15	15		-
Direção e mergulho	-12	- 6	- 6		-
RMR	100	36	44		-
CLASSE >>		IV	III		-

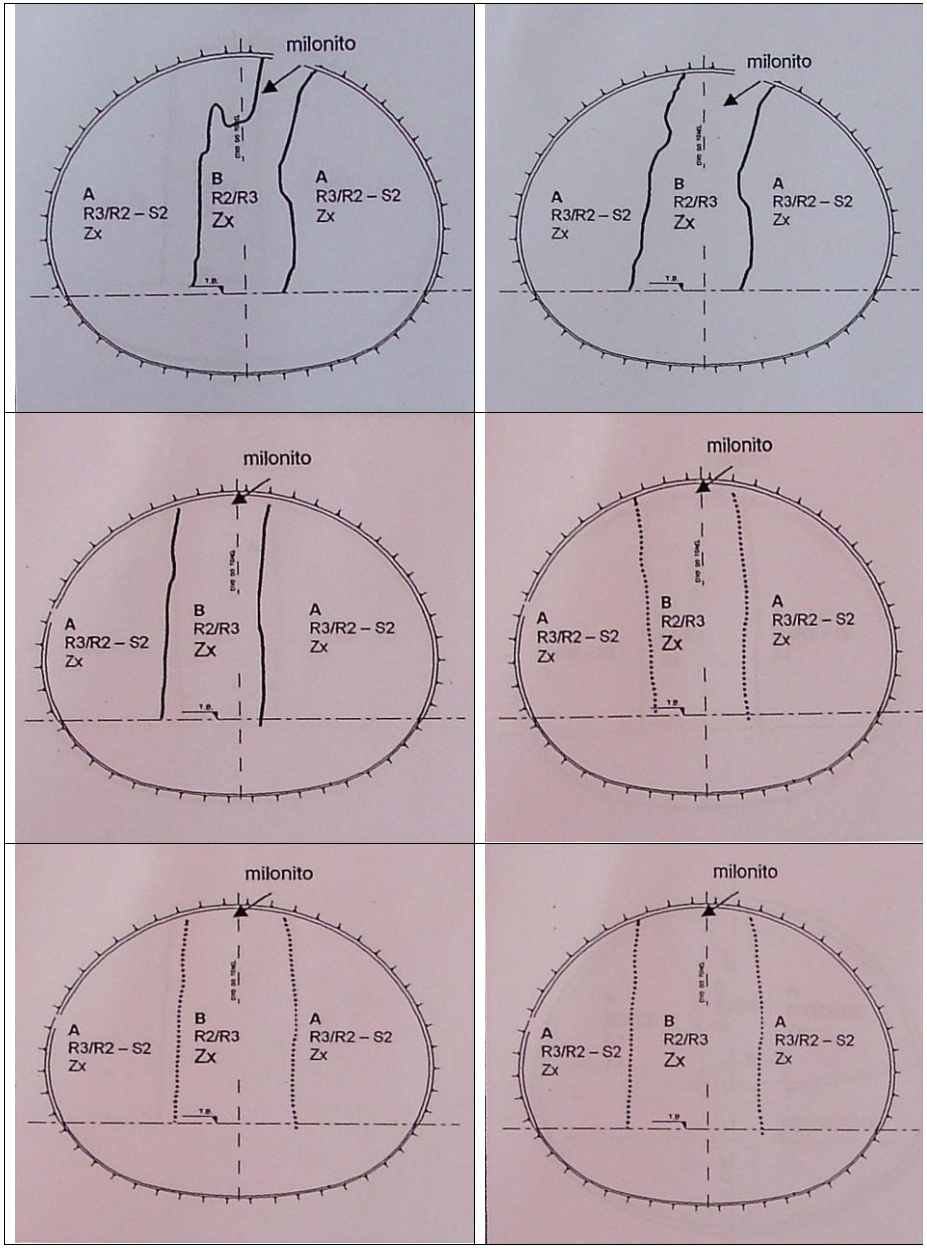
ACOMPANHAMENTO DAS CLASSES DE MACIÇO DETERMINANTES DA ESTABILIDADE		
PROJETO EXECUTIVO	AVANÇO ANTERIOR	ATUAL
	IV(36)	IV(36)
COBERTURA DE ROCHA ACIMA DA ABÓBADA		
PREVISTA NO EXECUTIVO	ATUAL (Quando for possível determinar com furos táticos ou pela avaliação dos mapeamentos)	
-	-	

ha é de propriedade da Companhia do Metrô e seu conteúdo não pode ser copiado ou revelado a terceiros.
A liberação ou aprovação deste Documento não exime a projetista de sua responsabilidade sobre o mesmo.

Example of ATO face-mapping in cavern

RMR-parameter recordings, and joint set descriptions

-including clay in principal and secondary joints



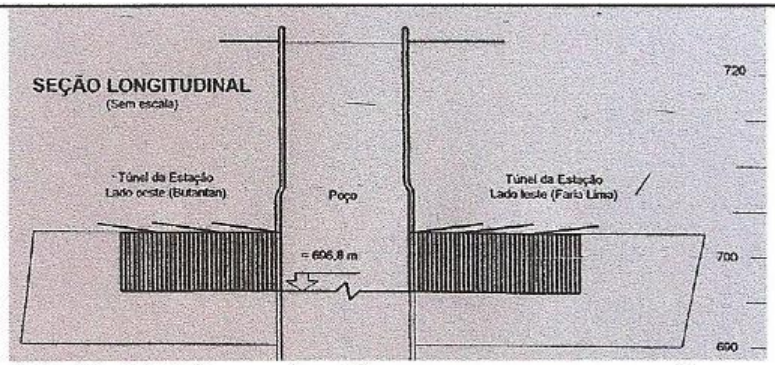
ROCK QUALITY LOGGING
(Six of the face logs)

The ‘core’ of better quality rock was indistinct close to the shaft

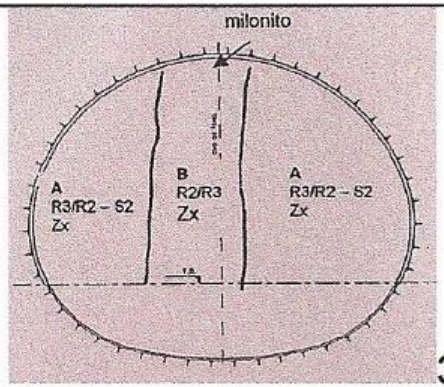
Increased volume of good rock in direction of Rua Capri (towards the East)

RMR rock class values of the 'core' (B) and the surrounding rock (A) on right.

Tassometer deformations were 15 mm and 21 mm at these locations



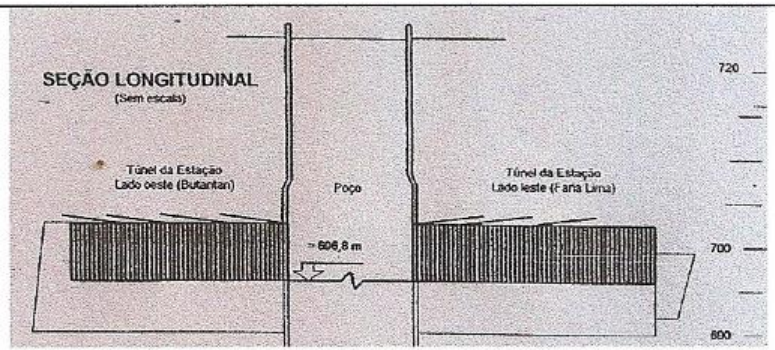
10.10.2006 (enfilagens suspensas)



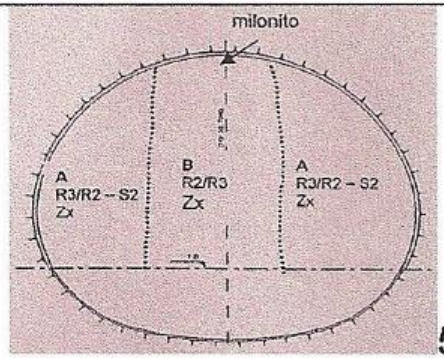
11.10.2006 39 cambotas 7110 m

A)
RMR = 35
= IV

B)
RMR = 44
= III



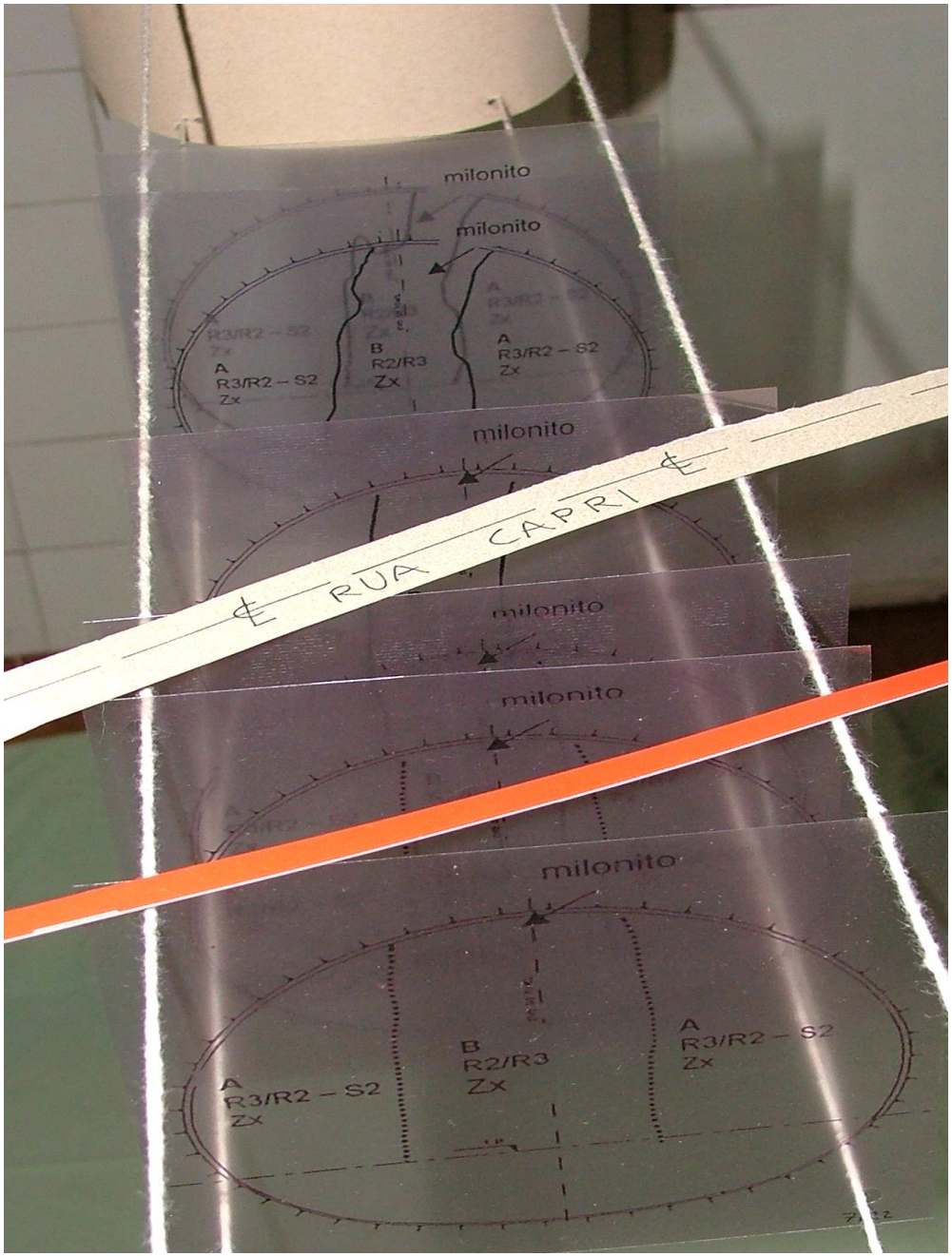
31.10.2006 (enfilagens suspensas)



27.10.2006 56 cambotas 7126.3 m

A)
RMR = 36
= IV

B)
RMR = 44
= III



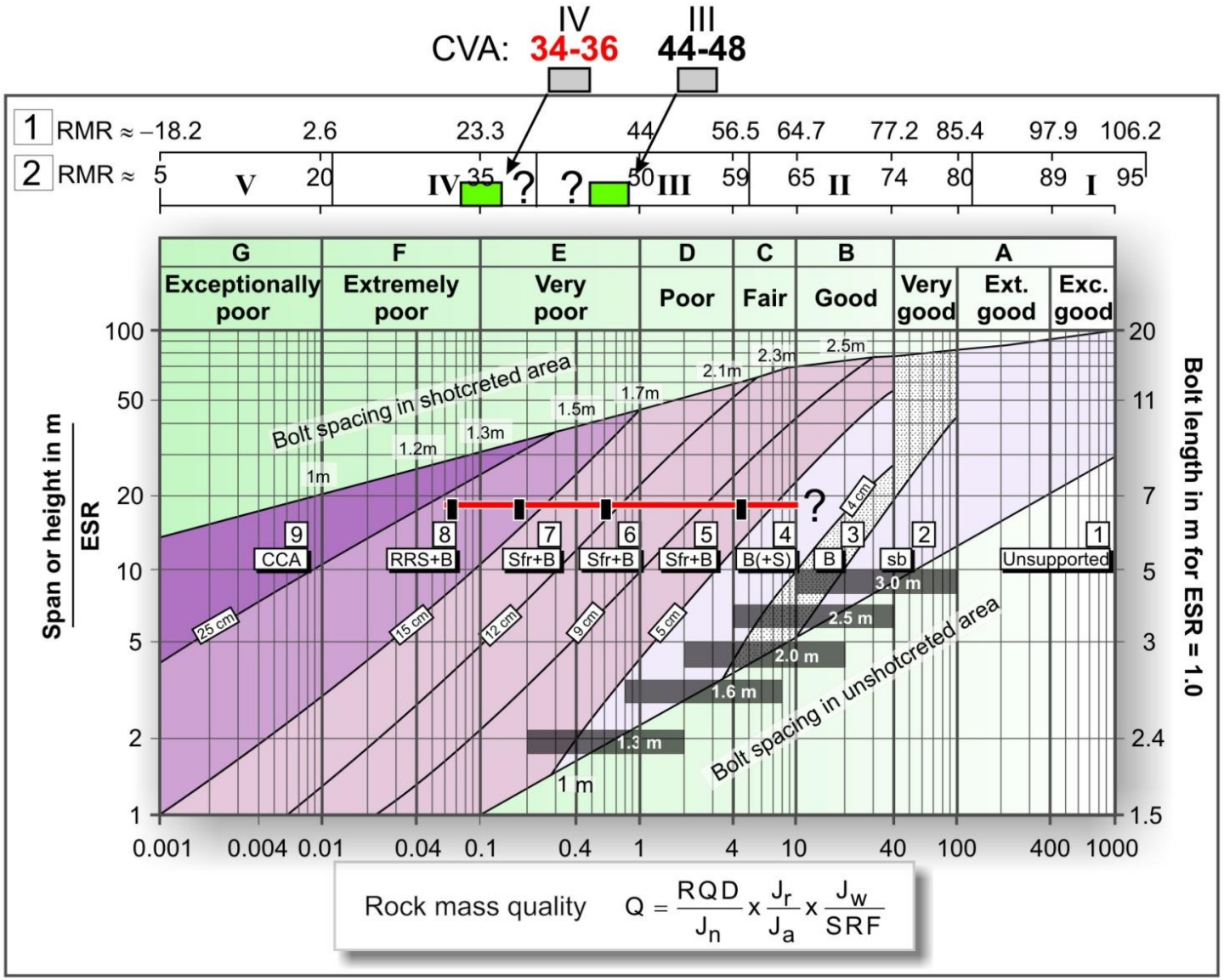
Increased volume of better Class III rock as Rua Capri was approached.

(Reduced grout take was consistent with this).

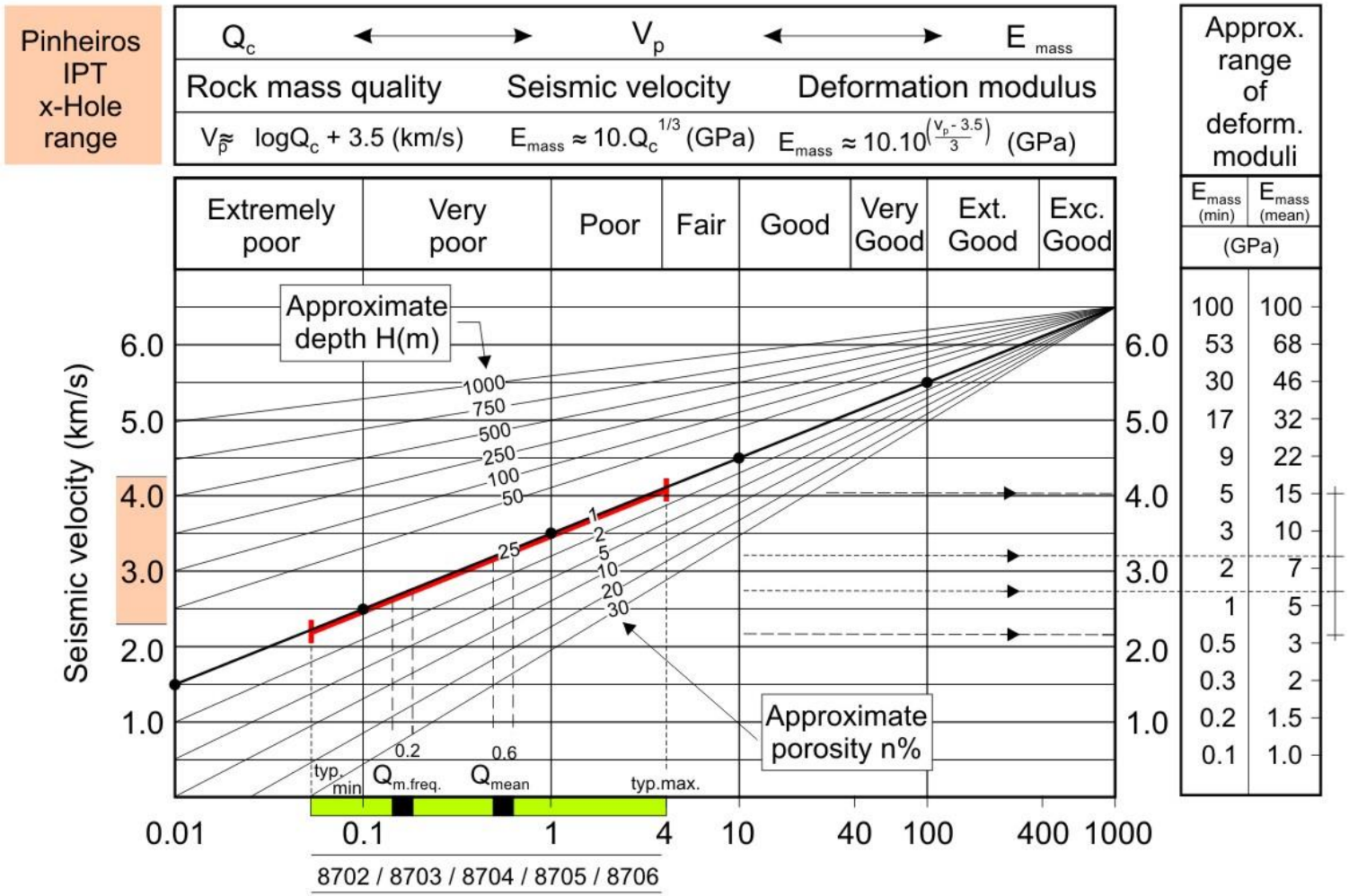
(NB string model,
8th Feb 2007)

Independent core-logging , following collapse; Q – range ≈ 0.1 to 4, was similar to cavern logging, and similar to IPT logging for São Paulo Metrô from 1996-1997.

(Q-system designed support B + S(fr) + RRS would also have collapsed).



Approximate correspondence between IPT cross-hole seismic , about 100 m distant, and Q-logging results for five nearest boreholes

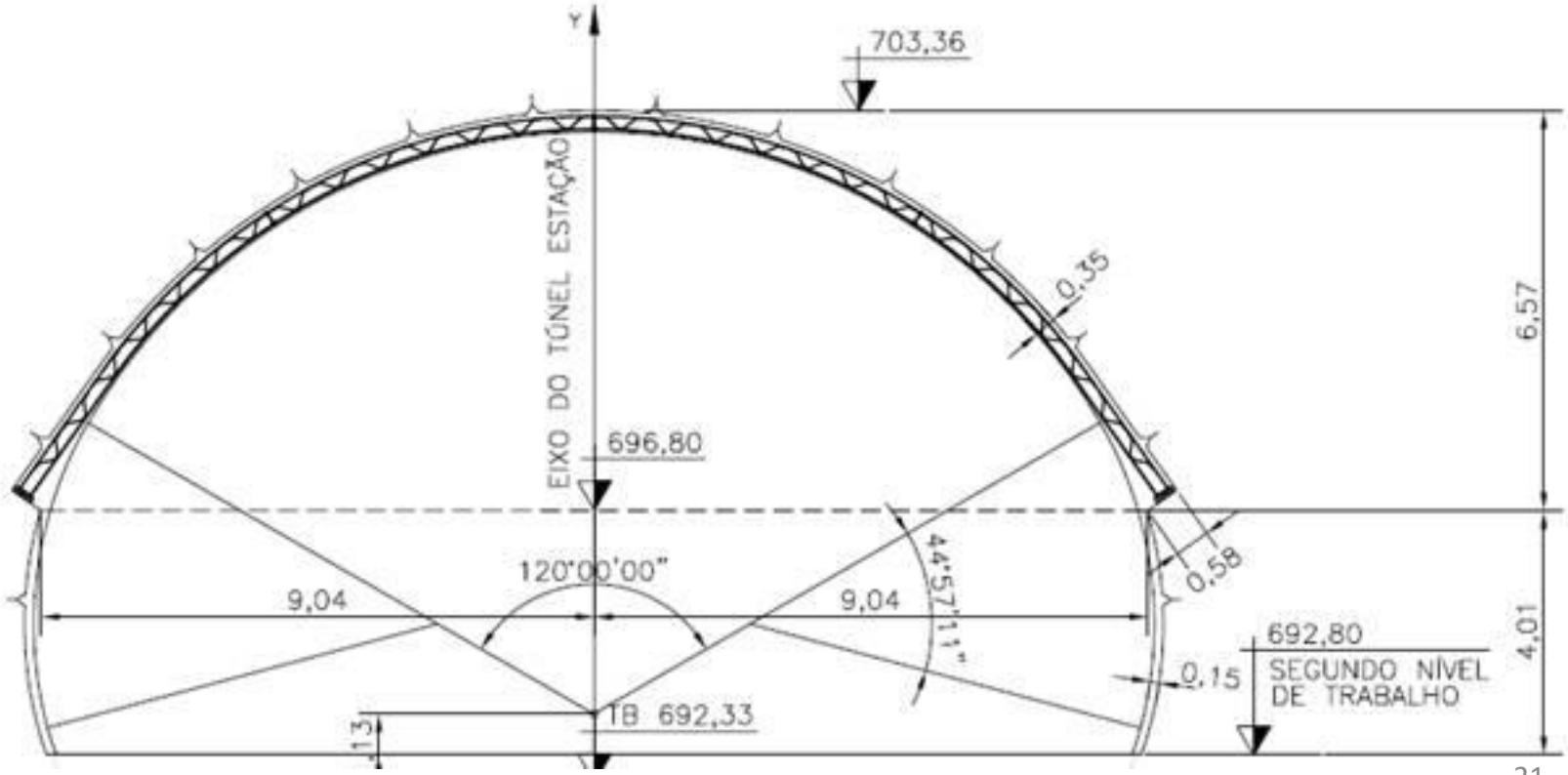


$$Q_c = \left[\frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \right] \frac{\sigma_c}{100}$$

Assume σ_c= 100 MPa

HEAVY PRIMARY SUPPORT WAS USED FOR THE STATION ARCH

Cambota and recessed ‘elephant-feet’ supported the top heading



Due to assumed low rock cover (3 m):
lattice girders @ 0.85 m c/c + ≥ 35 cm S(fr)

(A cheaper B+S(fr) design was rejected)

AN EXAMPLE OF THE INSTRUMENTATION – CENTRAL EXTENSOMETERS

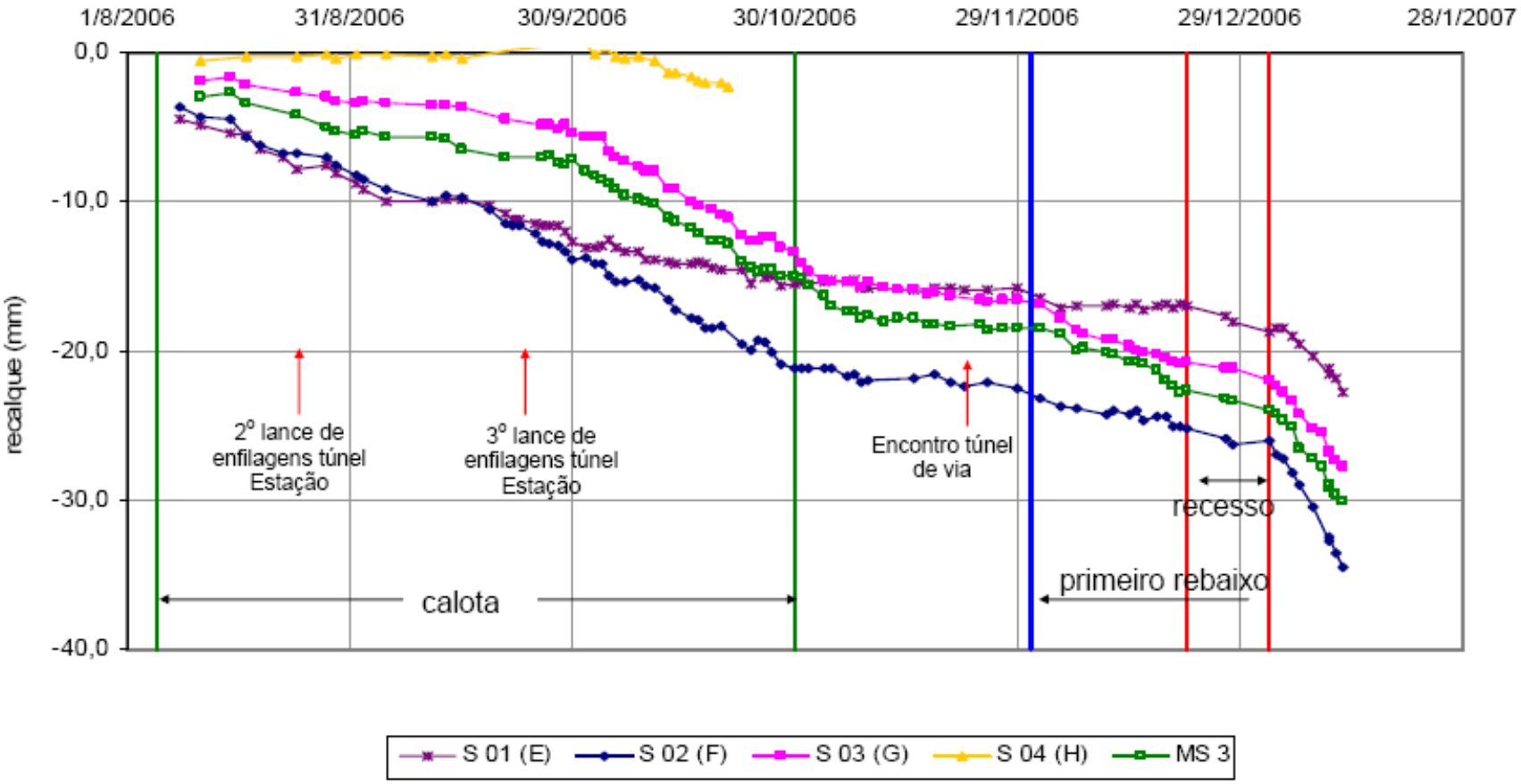
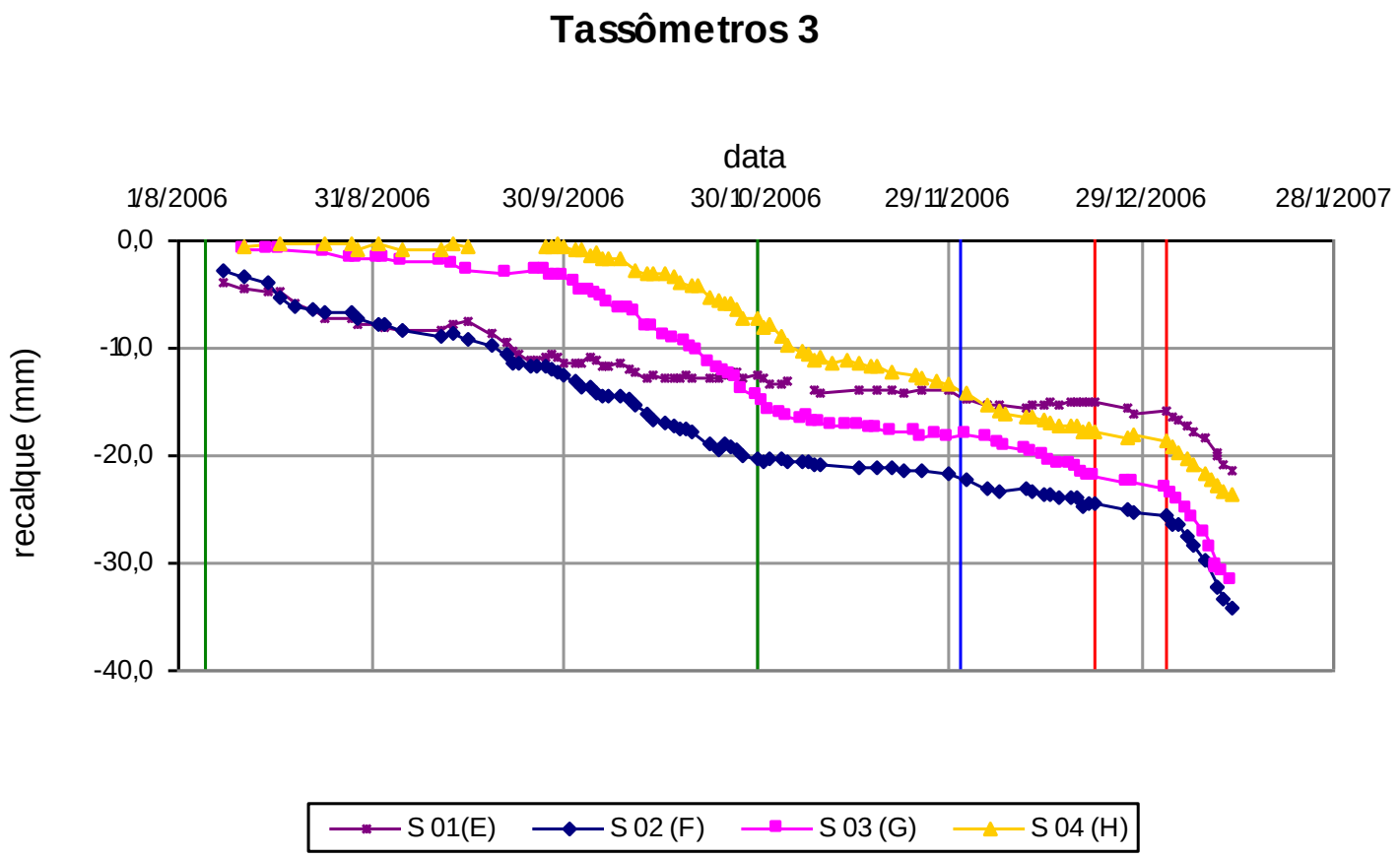


Gráfico 115. Recalque em função do tempo tassômetros 2 (central)

Top heading deformation levels are of 'expected magnitudes' before the failure process began, if one chooses to use the Q-system empirical links between deformation and Q-value.

(UDEC modelling gave similar magnitudes, i.e. approx. 17-22 mm)



Empirical estimation of expected magnitudes of deformation

(from Barton, 2002)

Q_{mean} from the five borehole cores nearest to the cavern. Note: σ_v and σ_h are estimates of the vertical and horizontal stress, based on an assumed (weighted) mean density for soil/saprolite/rock of 2.4 t/m³ and a depth of 25 m.

In this example $\sigma_v = \sigma_h$ (K_0 =1) is assumed.

The SPAN and HEIGHT of the station cavern are in millimetres).

$$\Delta_v = \frac{\text{SPAN}}{100Q}\sqrt{\frac{\sigma_v}{\sigma_c}} \quad (20)$$

$$\Delta_h = \frac{\text{HEIGHT}}{100Q}\sqrt{\frac{\sigma_h}{\sigma_c}} \quad (21)$$

Therefore we can also give an approximation for $k_0 = \sigma_h/\sigma_v$ as follows:

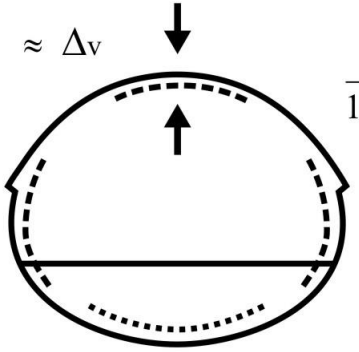
$$k_0 = \left(\frac{\text{SPAN}}{\text{HEIGHT}}\right)^2 \left(\frac{\Delta_h}{\Delta_v}\right)^2 \quad (22)$$

Units in Eqs. (20)–(22) are as follows: SPAN, HEIGHT, Δ_v and Δ_h are each in millimetres, while rock stresses and rock strengths need consistent units such as MPa.

$$\Delta_v \approx \frac{\text{SPAN}}{100.\text{Q}}\sqrt{\frac{\sigma_V}{\sigma_c}} \quad // \quad \frac{\gamma H}{100}\left\{\begin{matrix}\text{soil} & - \\ \text{saprolite} & \\ \text{rock} & -\end{matrix}\right\} 25\text{ m}$$

$$\frac{18{,}000}{100 \text{ x } 0.63}\sqrt{\frac{25 \, x \, 2.4}{100 \, x \, 100 \, MPa}} \Rightarrow \underline{\underline{22 \, mm}}$$

≈ Δv



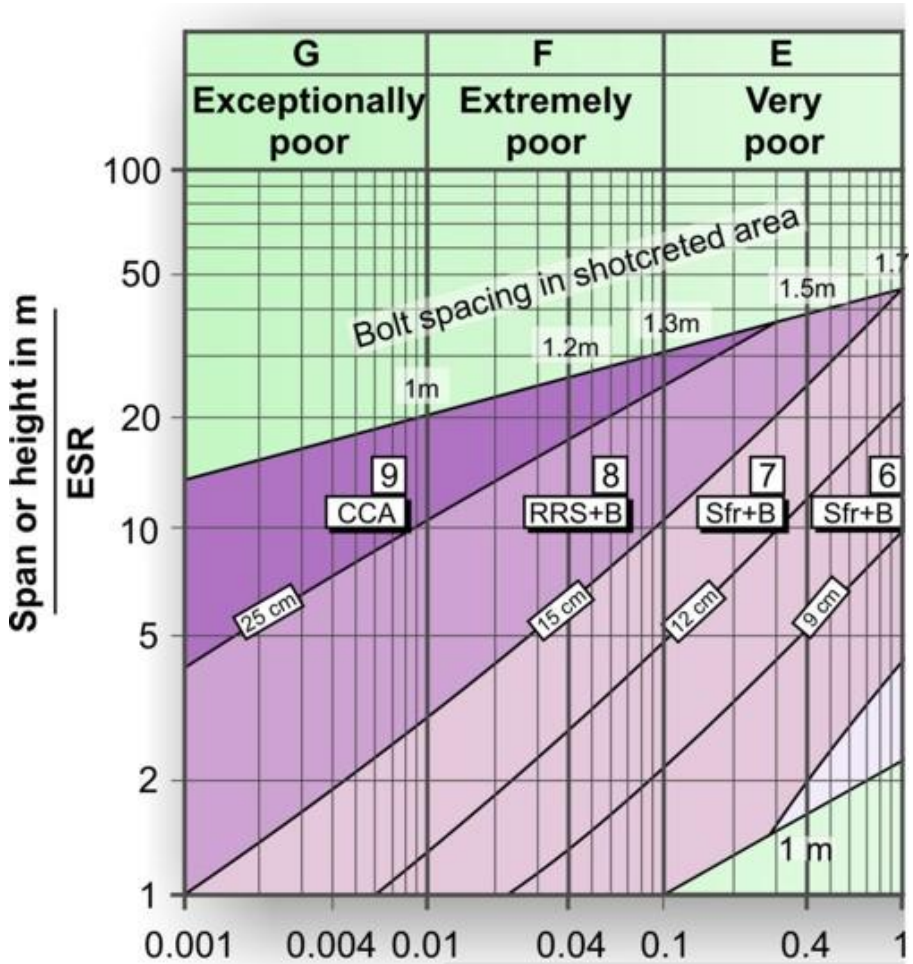
‖ ?

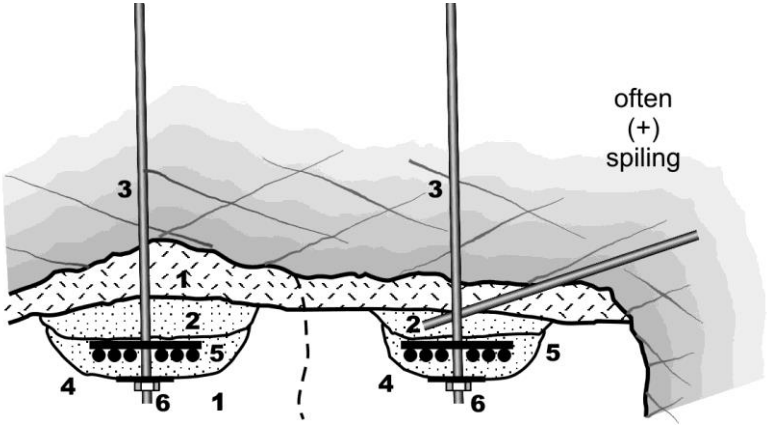
≈ 1/2 Δh

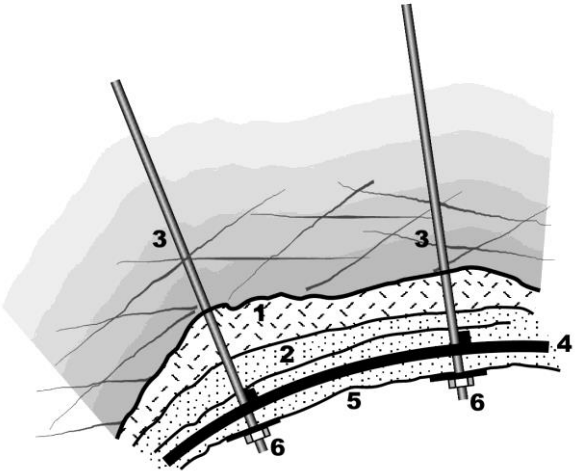
$$\Delta_h \approx \frac{\text{HEIGHT}}{100.\text{Q}}\sqrt{\frac{\sigma_h}{\sigma_c}} \quad \left(\begin{matrix}\text{assume} \\ \sigma_v = \sigma_h\end{matrix}\right)$$

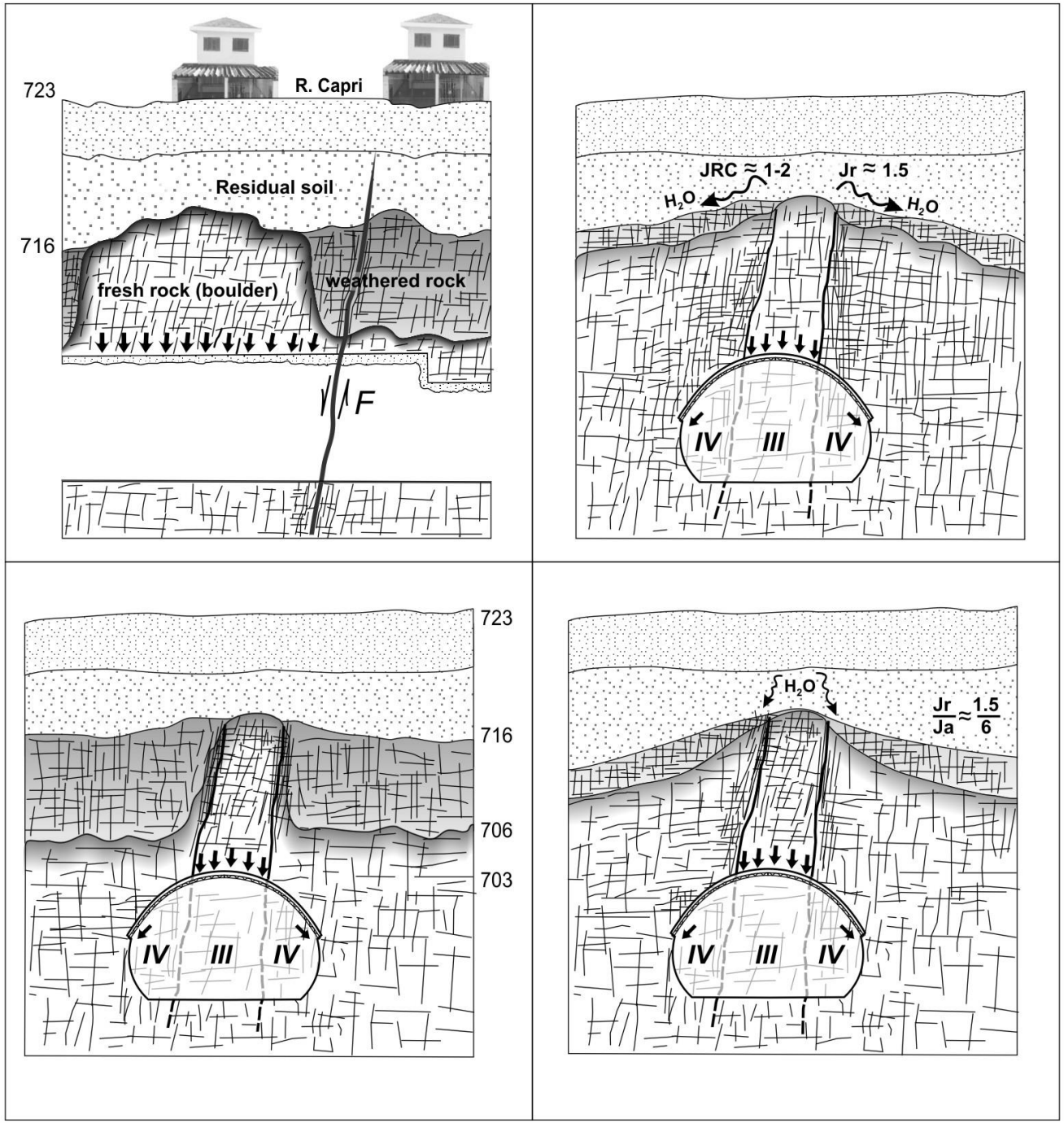
$$\frac{14{,}000}{100 \text{ x } 0.63}\sqrt{(K_0 = 1)} \Rightarrow 22 \, x \, \frac{14}{18} = \underline{\underline{17 \, mm}}$$

One of the most robust support methods from the Q-system:
RRS (rib-reinforced-shotcrete) – would also have failed under the Pinheiros *ridge-of-rock* loads – *and there was assumed to be insufficient rock cover for efficient bolt action*



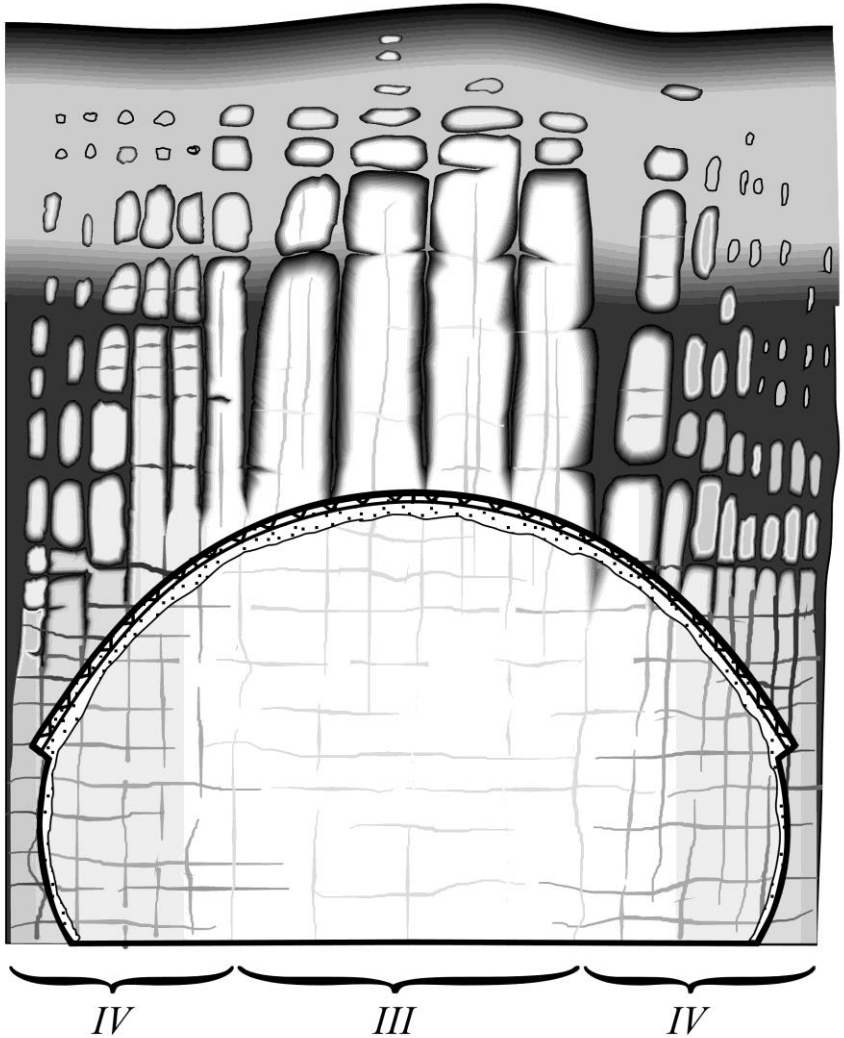




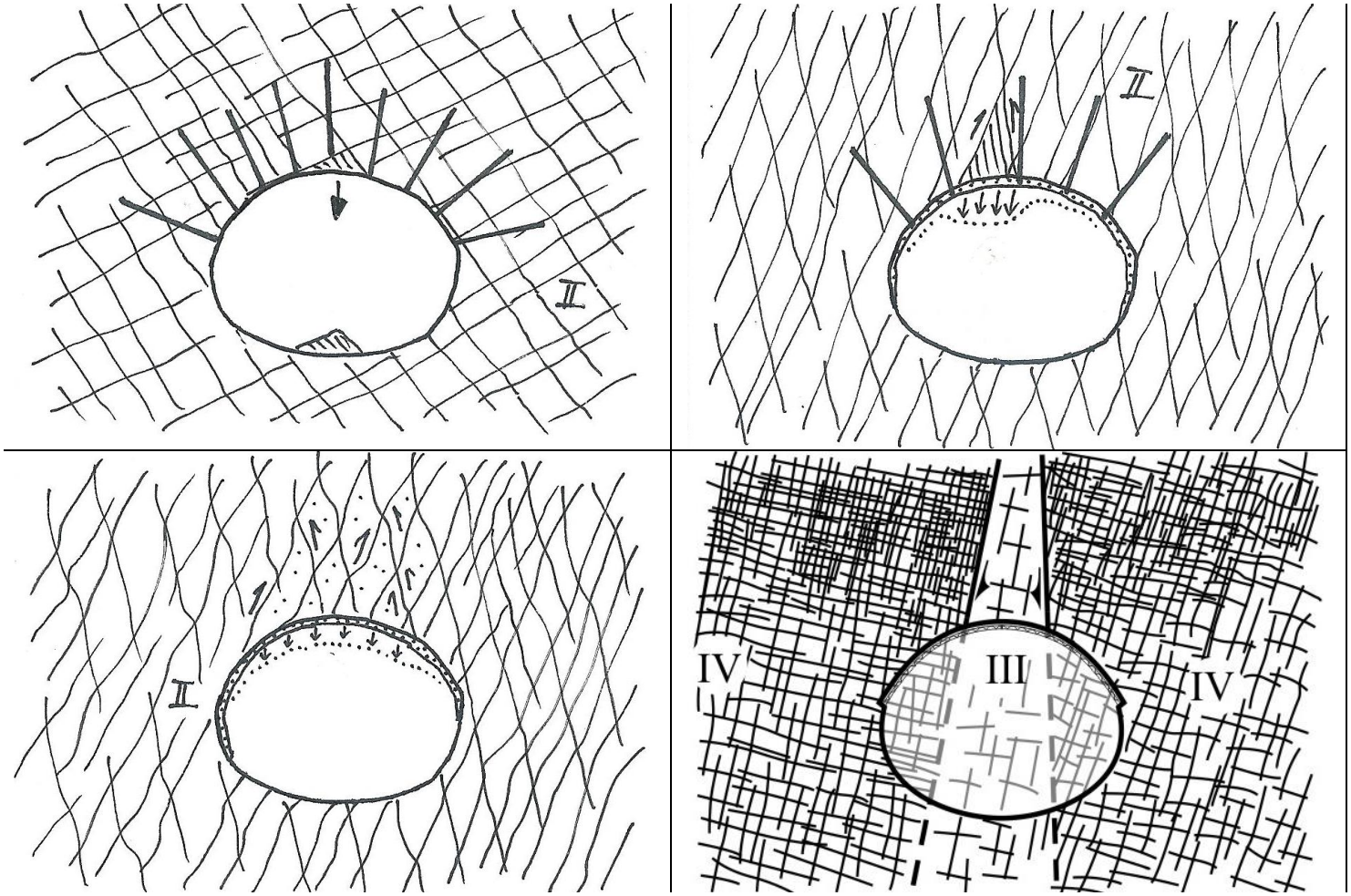


An imagined sequence of increasing sub-surface differential weathering

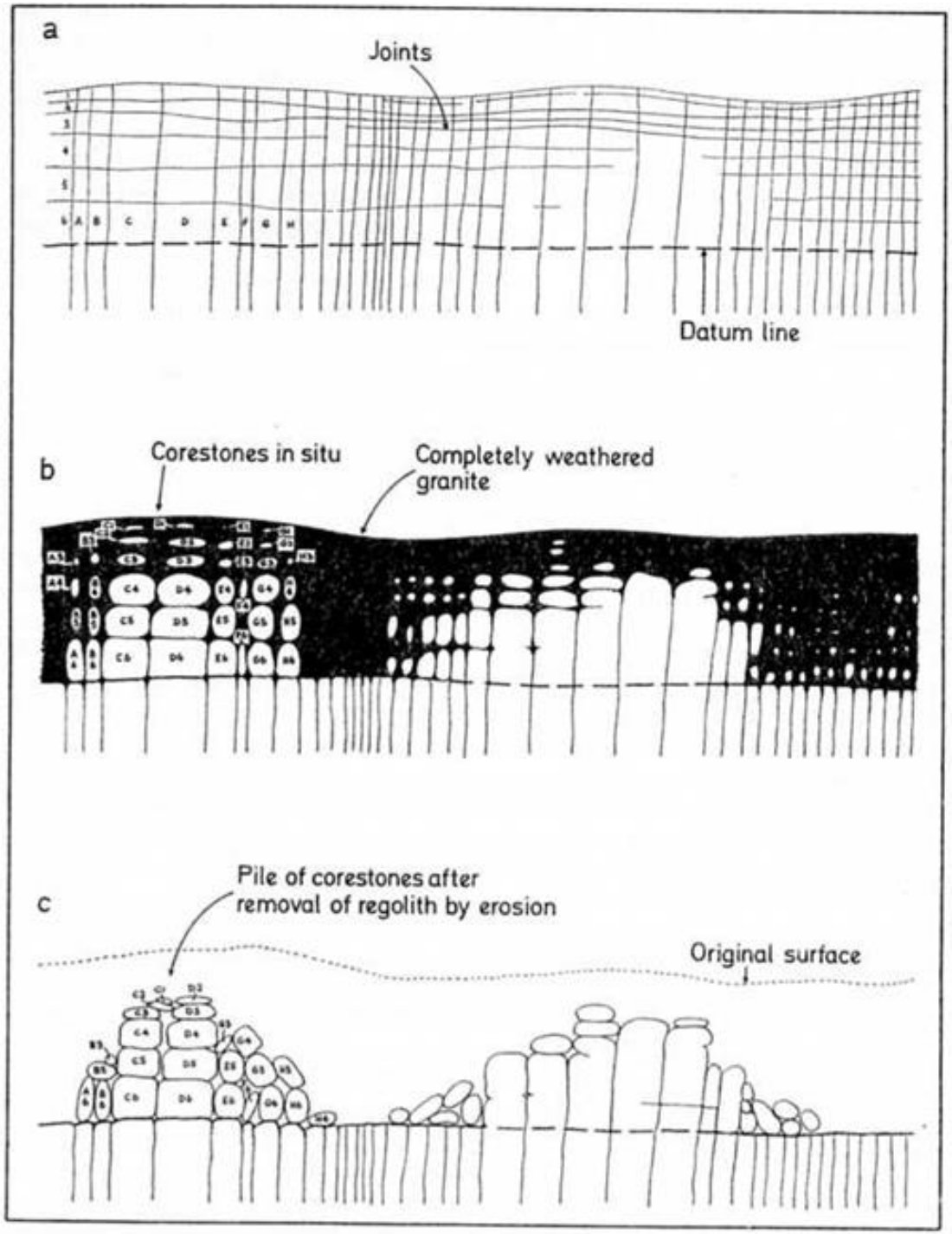
An advanced stage of weathering: a wedge-shaped ridge surrounded by clay



Wedges can take many forms, and create different loadings on the support

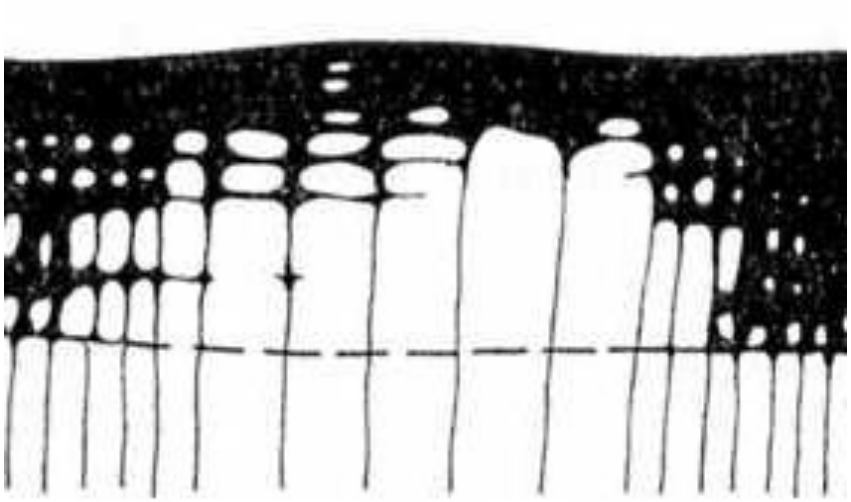


Relic joint structures in overlying saprolite assumed to have contributed to loading (illustrative example)

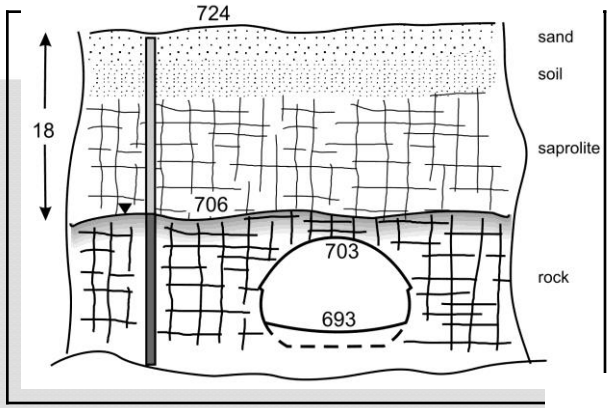

a
Joints
Datum line
b
Corestones in situ
Completely weathered granite
c
Pile of corestones after removal of regolith by erosion
Original surface

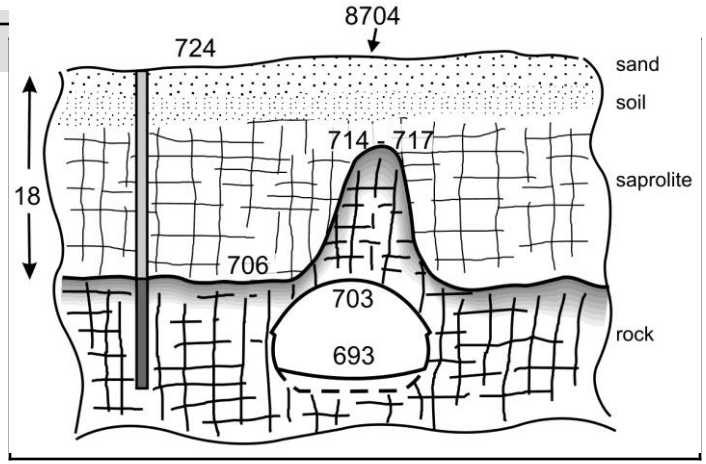
Linton, 1955

Core-stone phenomena in *massive granites* (extract from Linton, 1955…more jointing…deeper saprolite)



‘8704’?

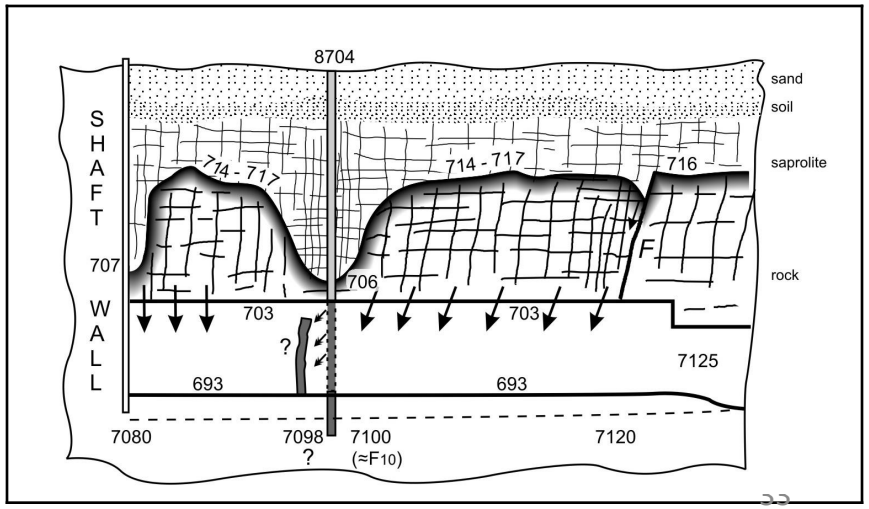




1. MEAN EXPECTATION
most holes drilled from 723-724 m, most rock at elev. 706-708 m.

2. POSSIBLE REALITY
most of collapsed rock fallen 10 m to 704-707 m.

3. FATED BOREHOLE 8704
(drilled at 7100 approx, reached rock at mean elev. 706 m.



POST-COLLAPSE EXCAVATION TO REVEAL LIKELY COLLAPSE MECHANISMS

Nominal elevation 704 m (1 m over cavern arch) on either side of the cavern

Fallen materials towards centre

Elevation 705-707 m. Example of fallen ‘core’ material.

Has fallen 9 to10 m but still has a top elevation of 706.5 m (approx.)

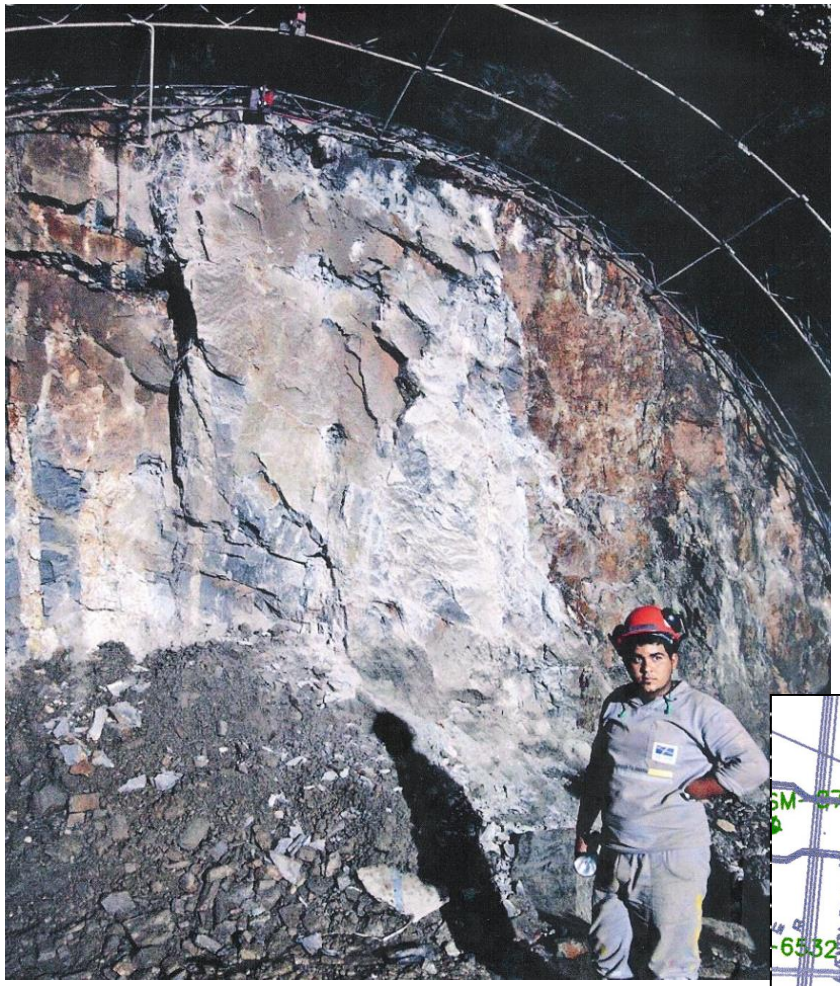
Previously at elevation ≈ 716 m, or ≈ *10 m* above assumed (drilling-determined) levels.

The smooth and weathered appearance of the edge of the fallen ridge-of-rock

Elev. 704 …… Ch. 7.0+80 m

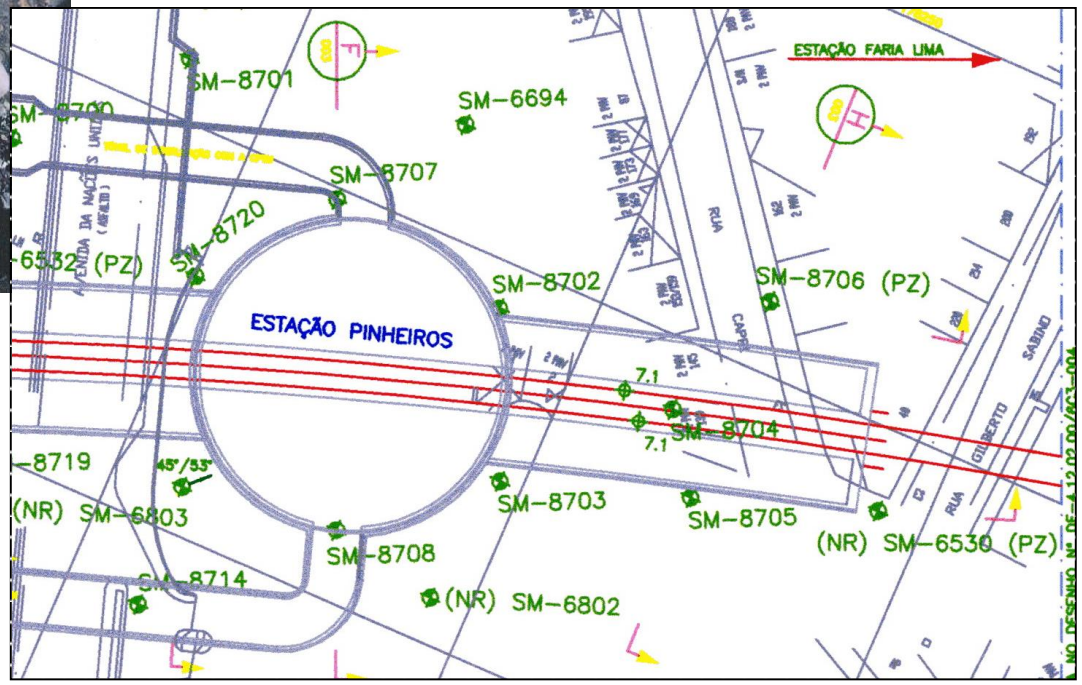
Elev. 704 …… Ch. 7.0+96.5 m ……. Each part of ridge after falling 9 to 10m

Elev. 704……Ch. 7.1+08 m



Ch. 7160 approx…….

……..ridge-of-rock follows cavern/tunnel for 80m



Folded lattice girders due to footing failure next to part of left wall

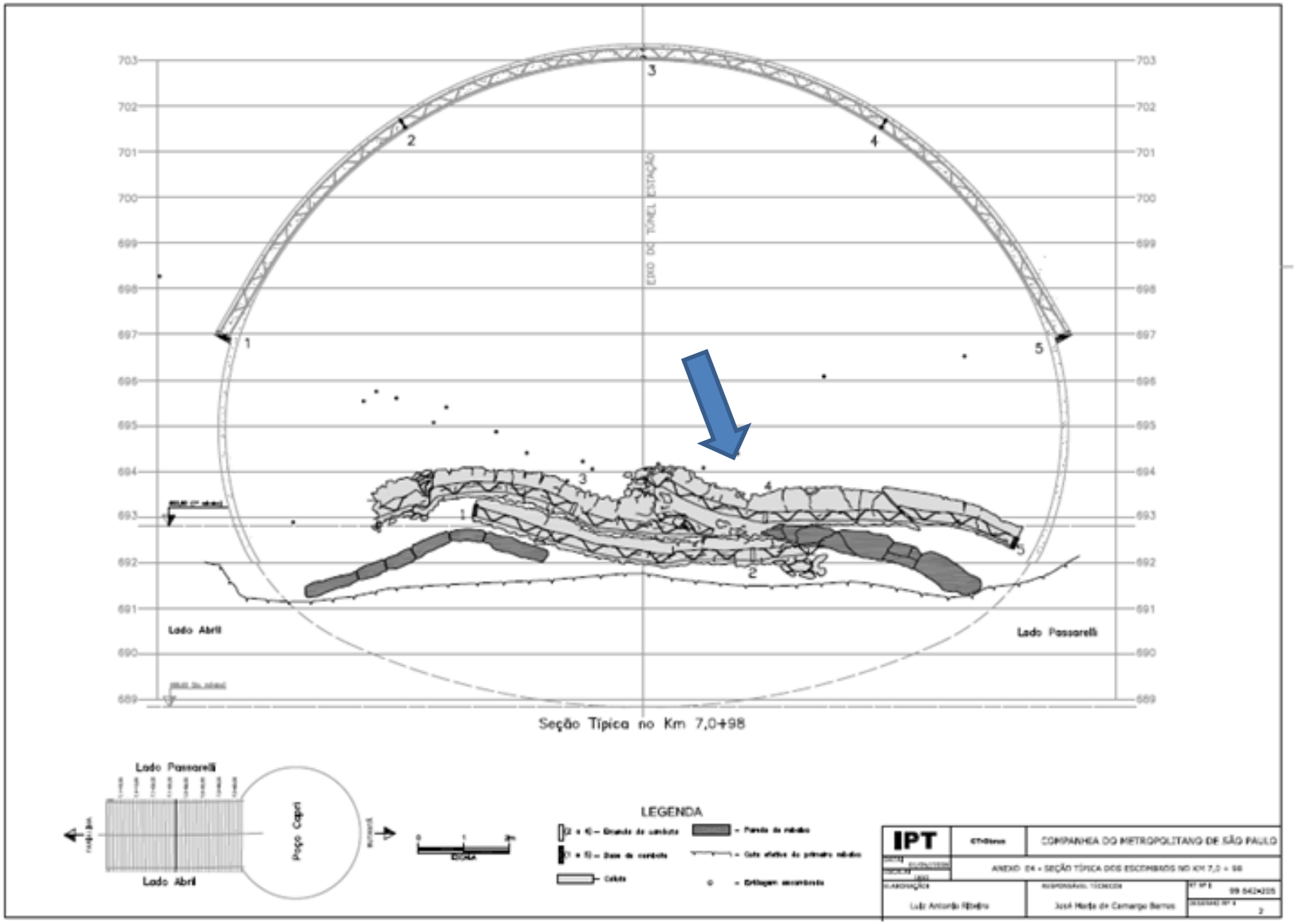
Pre-grouting tubing holds jointed rock ‘together’.

Evidence for 'elephant-footing' failure, due to inwards displacement of left wall S(mr). Rock fracturing?

Crushed excavator

Damage/crushing is indirect evidence of the many thousands of tons of fallen rock

Fallen and folded arch/wall/arch support (S/LG-Smr-S/LG)


703
702
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692
691
690
689
EIXO DO TÚNEL ESTAÇÃO
Lado Abril
Lado Passarelli
Seção Típica no Km 7,0+98
Lado Passarelli
Poço Capri
Lado Abril
LEGENDA
IPT
COMPANHEA DO METROPOLITANO DE SÃO PAULO
ANEXO: D4 - SEÇÃO TÍPICA DOS ESCOMBROS NO KM 7,0 + 98
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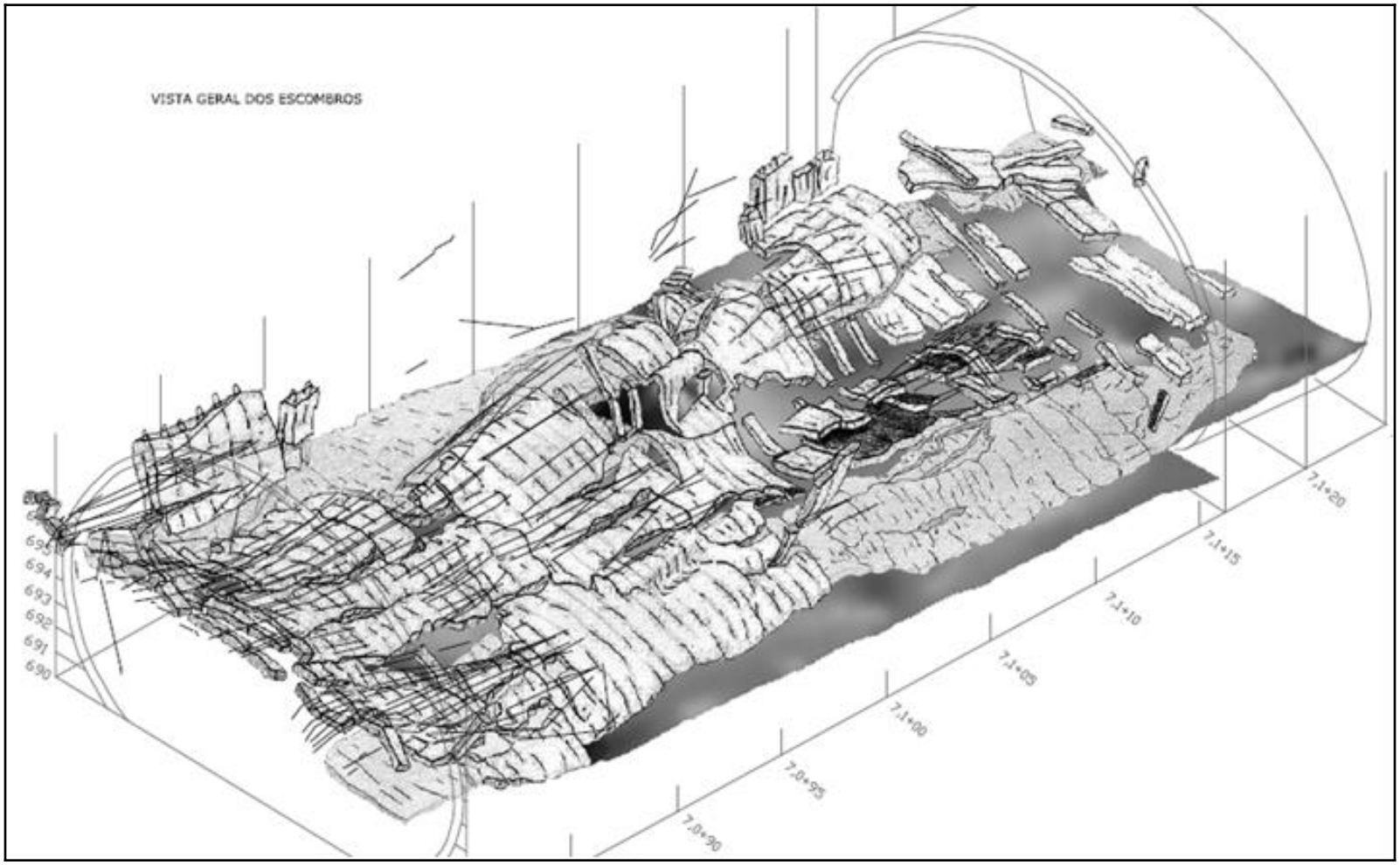
José Maria de Camargo Barros


VISTA GERAL DOS ESCOMBROS
695
694
693
692
691
690
7,0+90
7,0+95
7,1+00
7,1+05
7,1+10
7,1+15
7,1+20

Some investigations of the potential failure mechanisms using numerical models

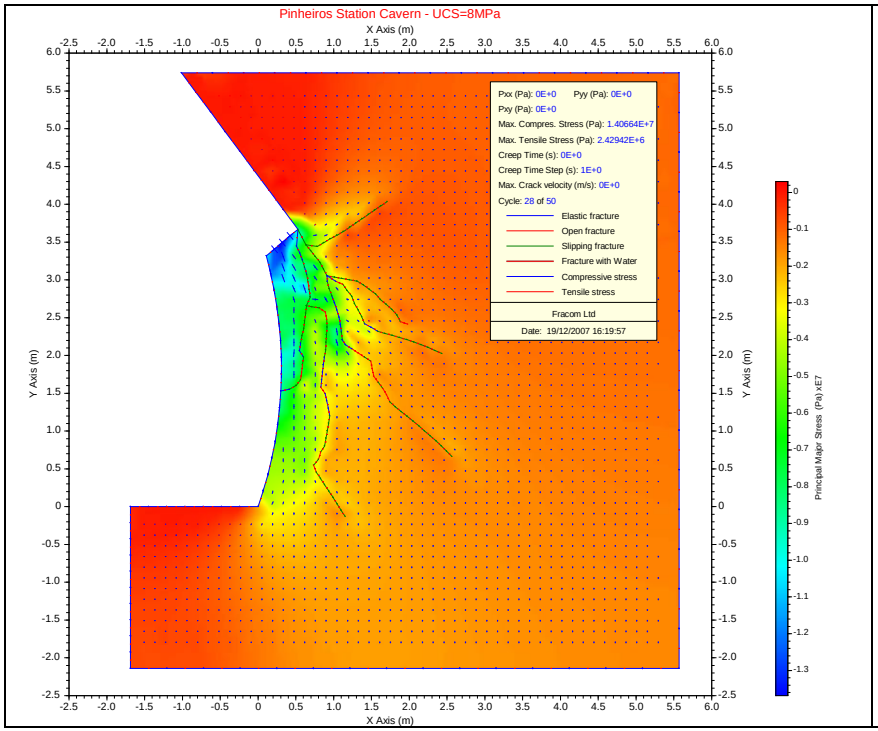
1. **FRACOD** for cracking below ‘elephant-footing.’ (Dr. Baotang Shen, Australia)

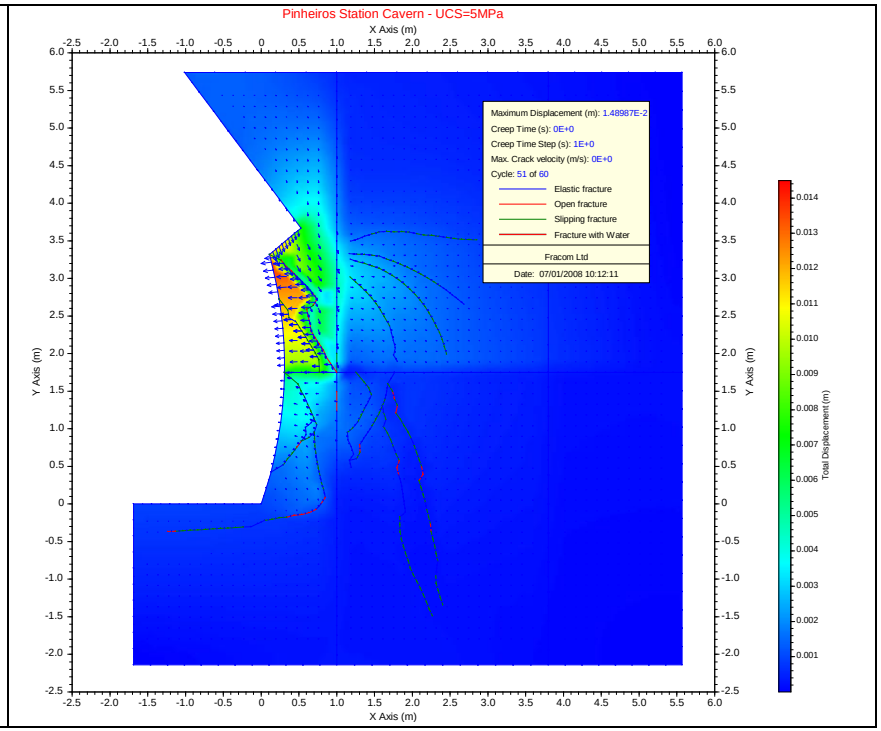
2. **UDEC** for overall cavern failure.

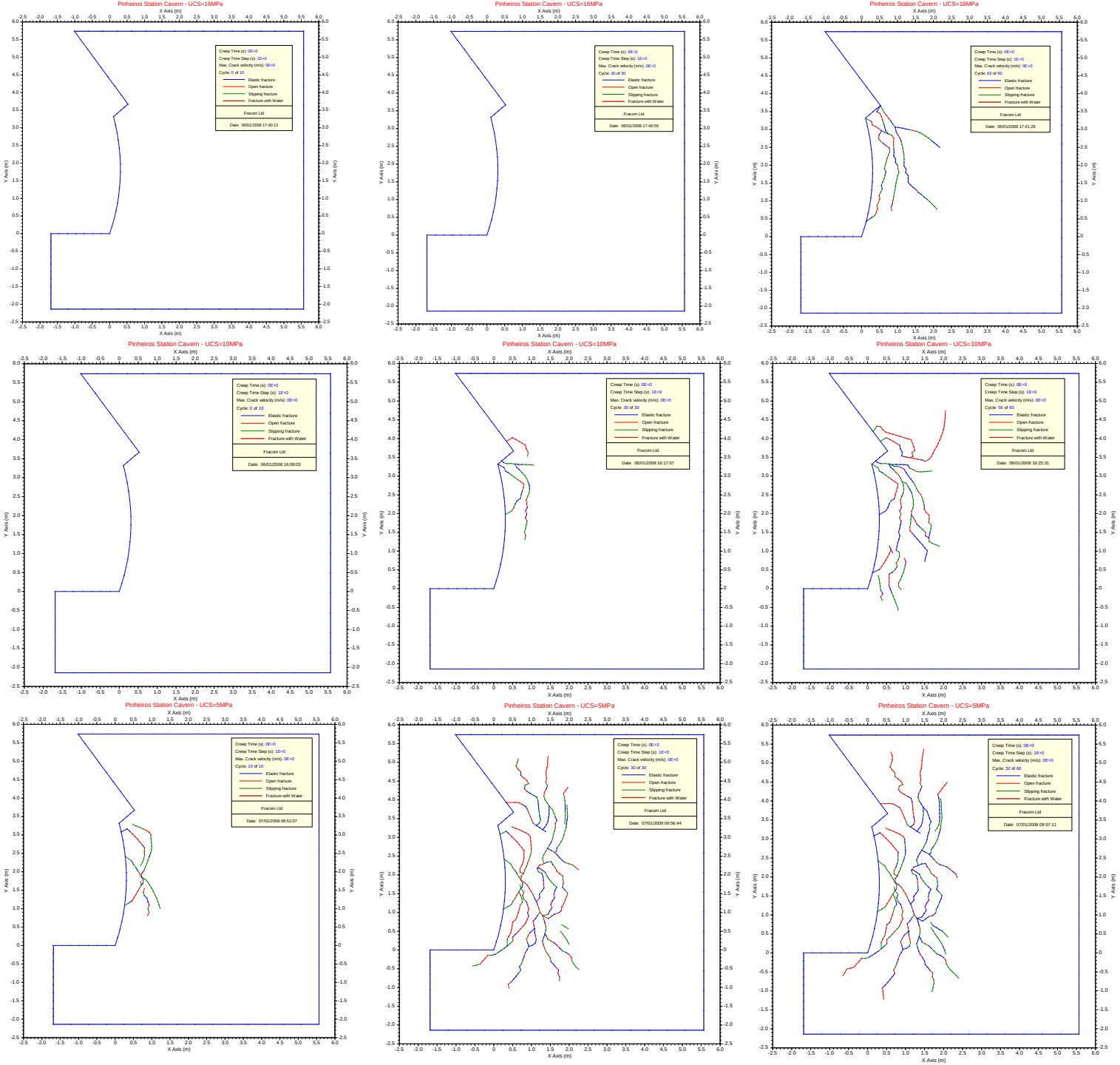
   (Dr. Stavros Bandis, Greece)

FRACOD modelling of possible rock cracking below ‘elephant-feet’

Examples of cracking WITHOUT and WITH joints present







FRACOD results:

three loading levels (2.5, 6 and 12 MPa)

three UCS assumptions (16, 10 and 5 MPa)

three deformation moduli assumptions (8, 5, 2.5 GPa)

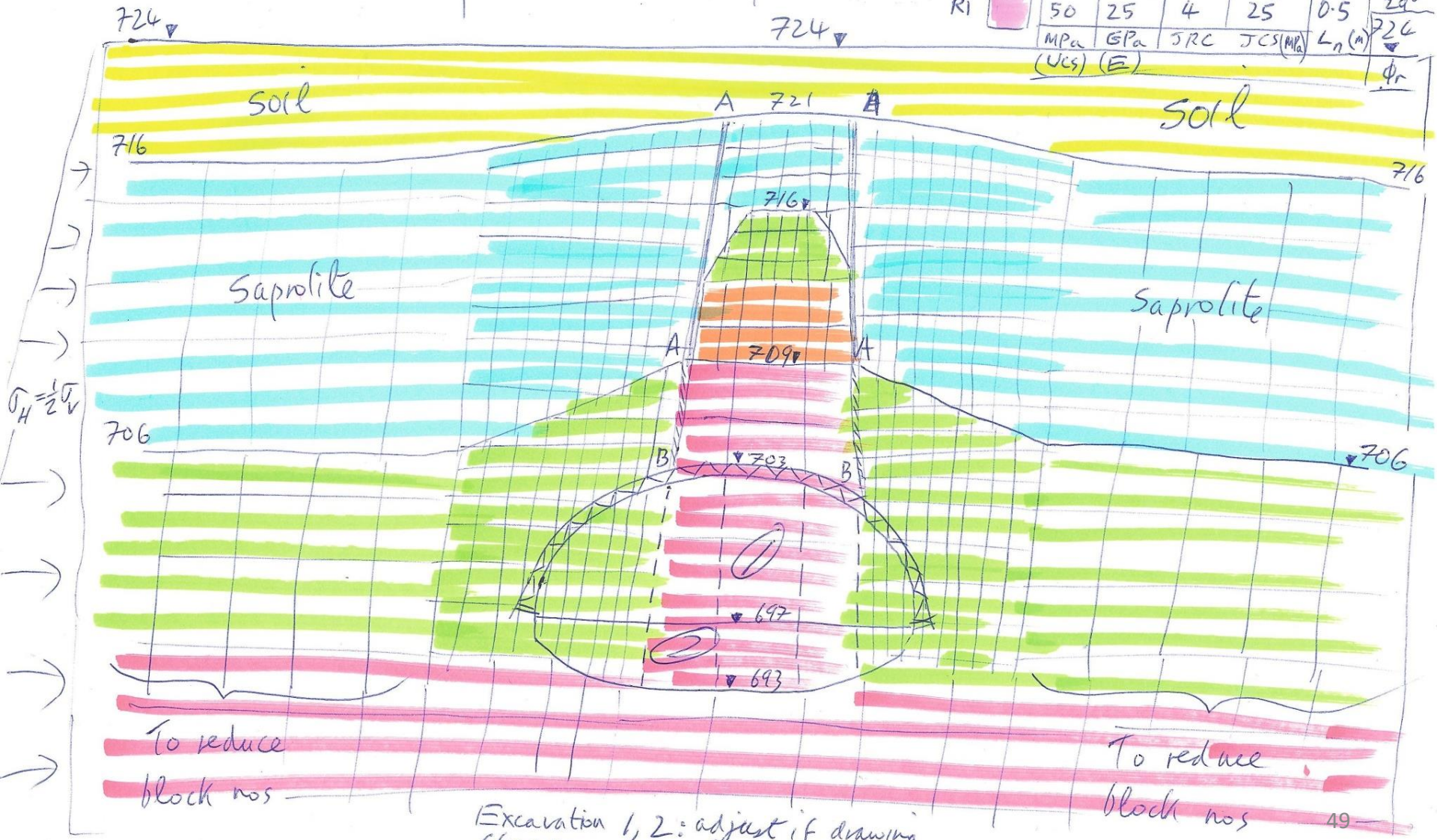
Input data suggestions to numerical modellers: Dr. Shen, Dr. Bandis

Very idealized – but please follow quite closely so "recognisable" principles

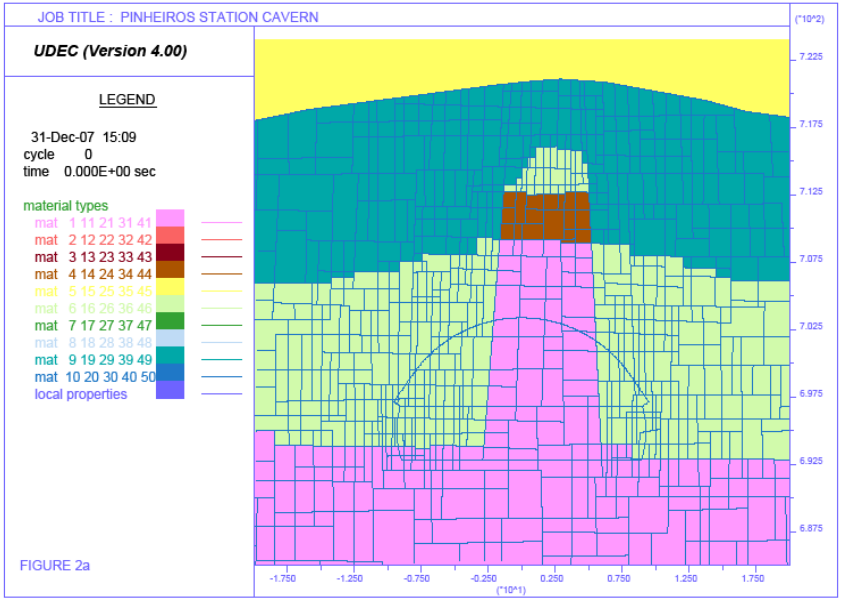
AAAA $\phi_r = 15°$ $c = 0$
AB AB $\phi_r = 20°$ $c = 0$

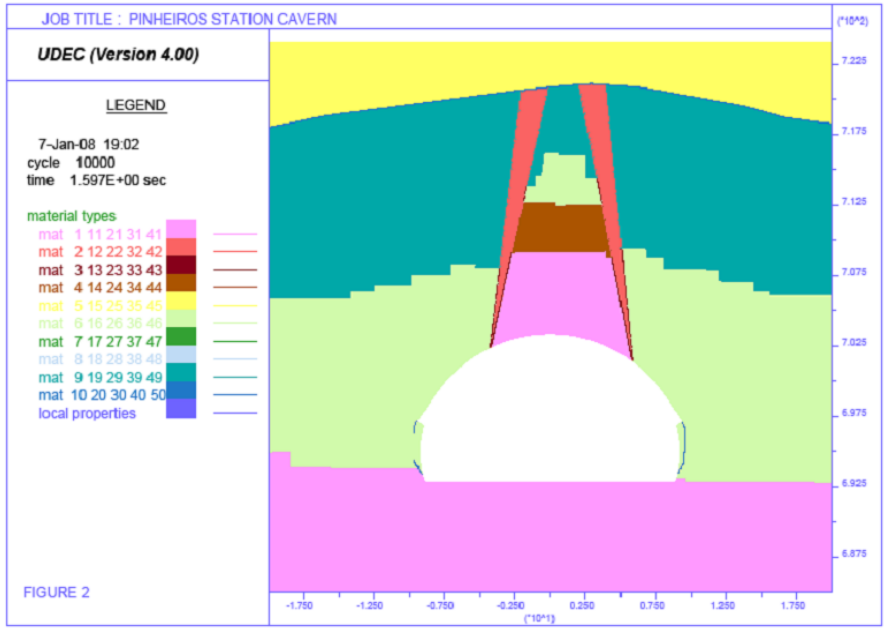
Guide to UCS, E, JRC, JCS ϕ_r

	UCS (MPa)	E (GPa)	JRC	JCS (MPa)	L_n (m)	ϕ_r
S1	0.1	0.05	–	–	–	15°
S2	1.0	0.5	2	0.5	0.2	20°
R3	10	5	2	5	0.3	25°
R2	20	12.5	3	10	0.4	27°
R1	50	25	4	25	0.5	29°

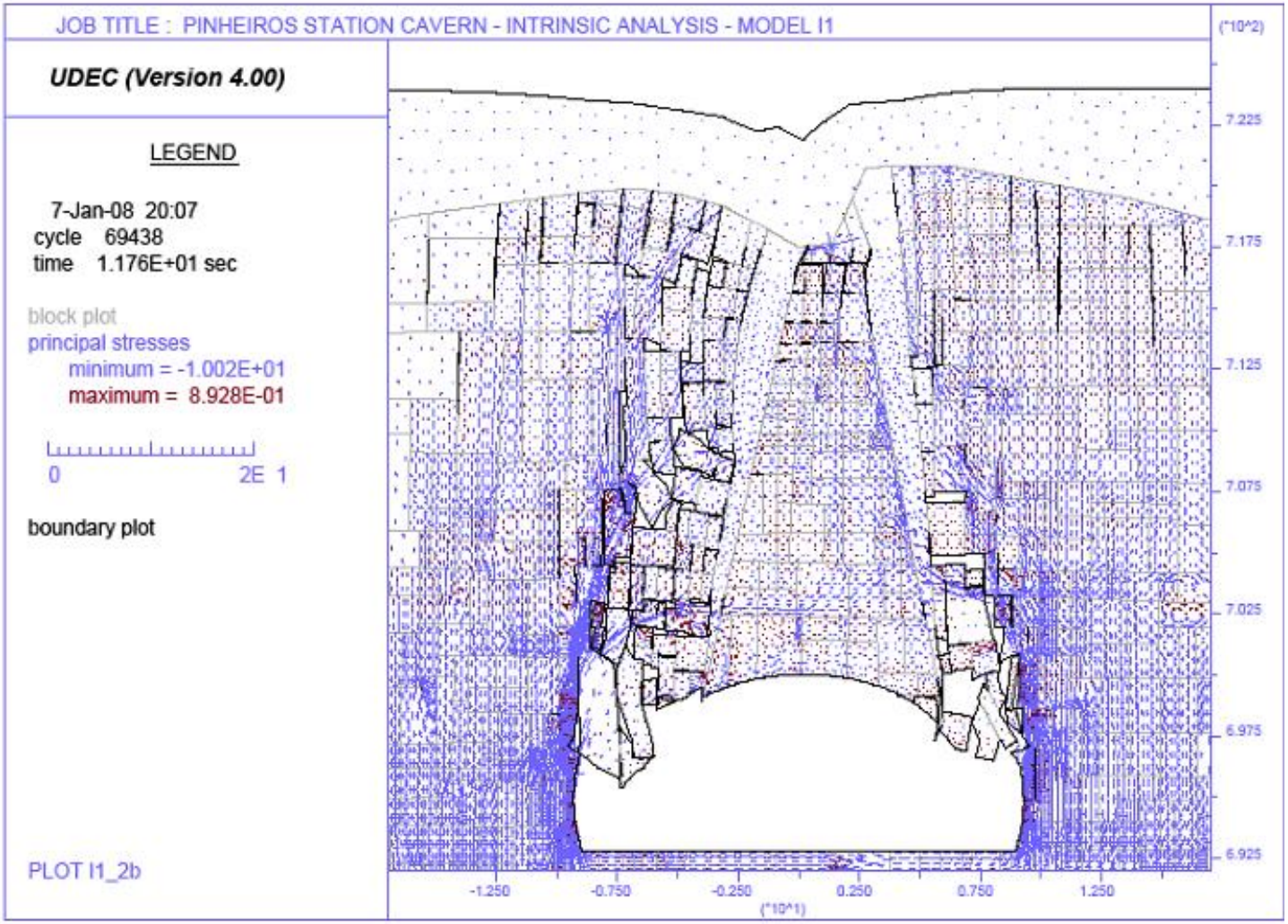


*The **UDEC** model on the left did not give collapse: the increasingly thick wedge of weathered material (red colour) seen on the right was required to allow failure*

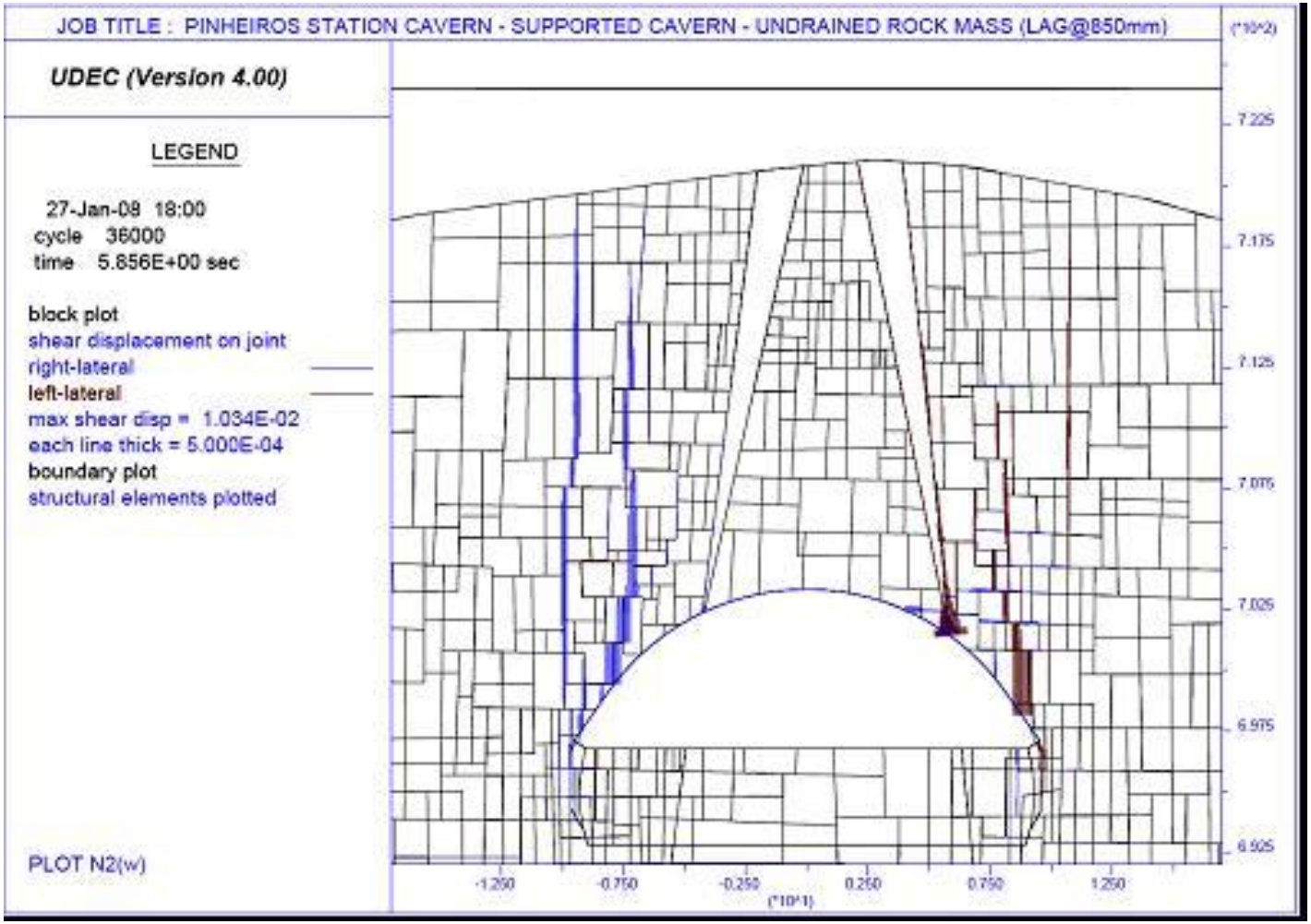




Preliminary modelling without rock support

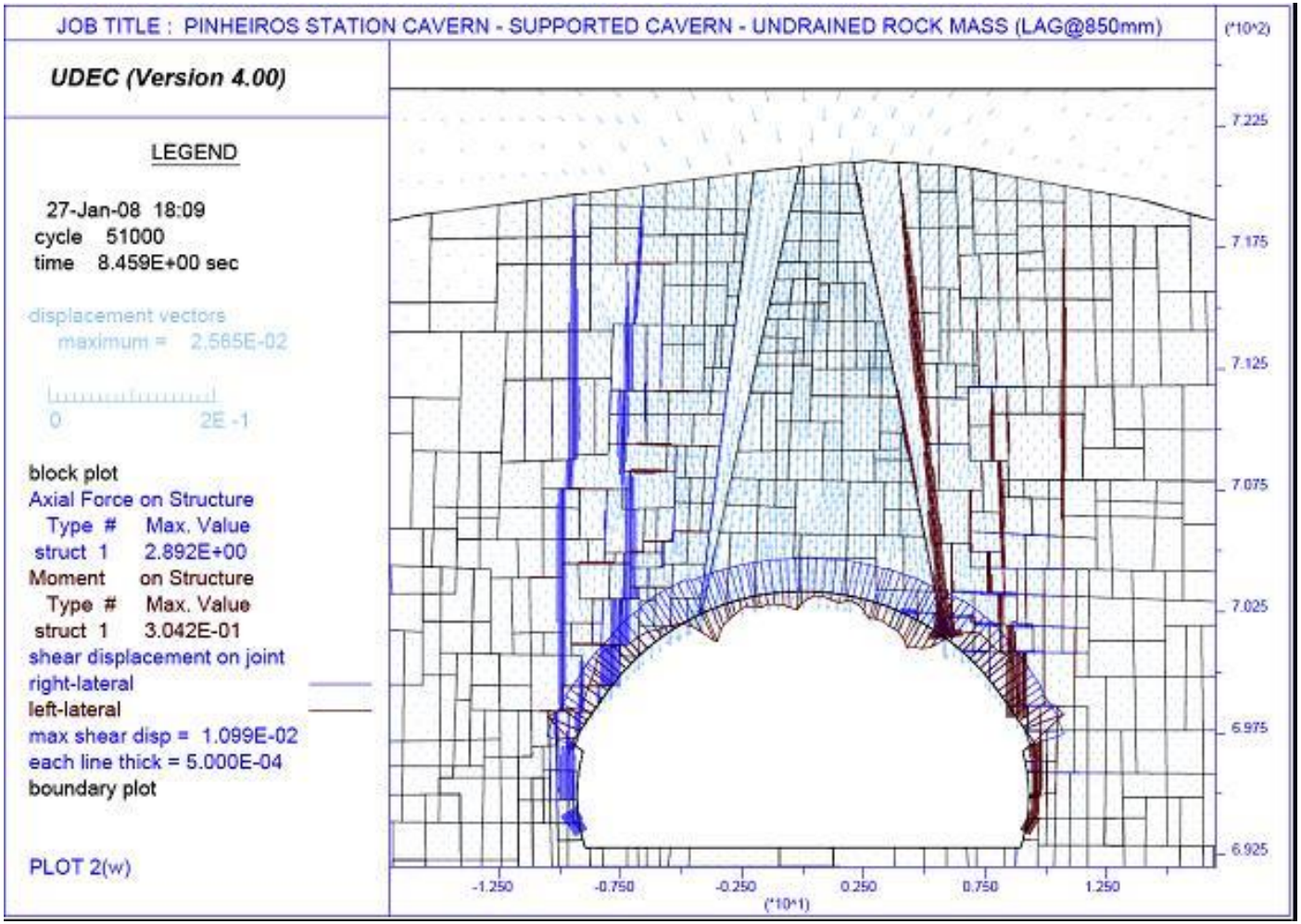


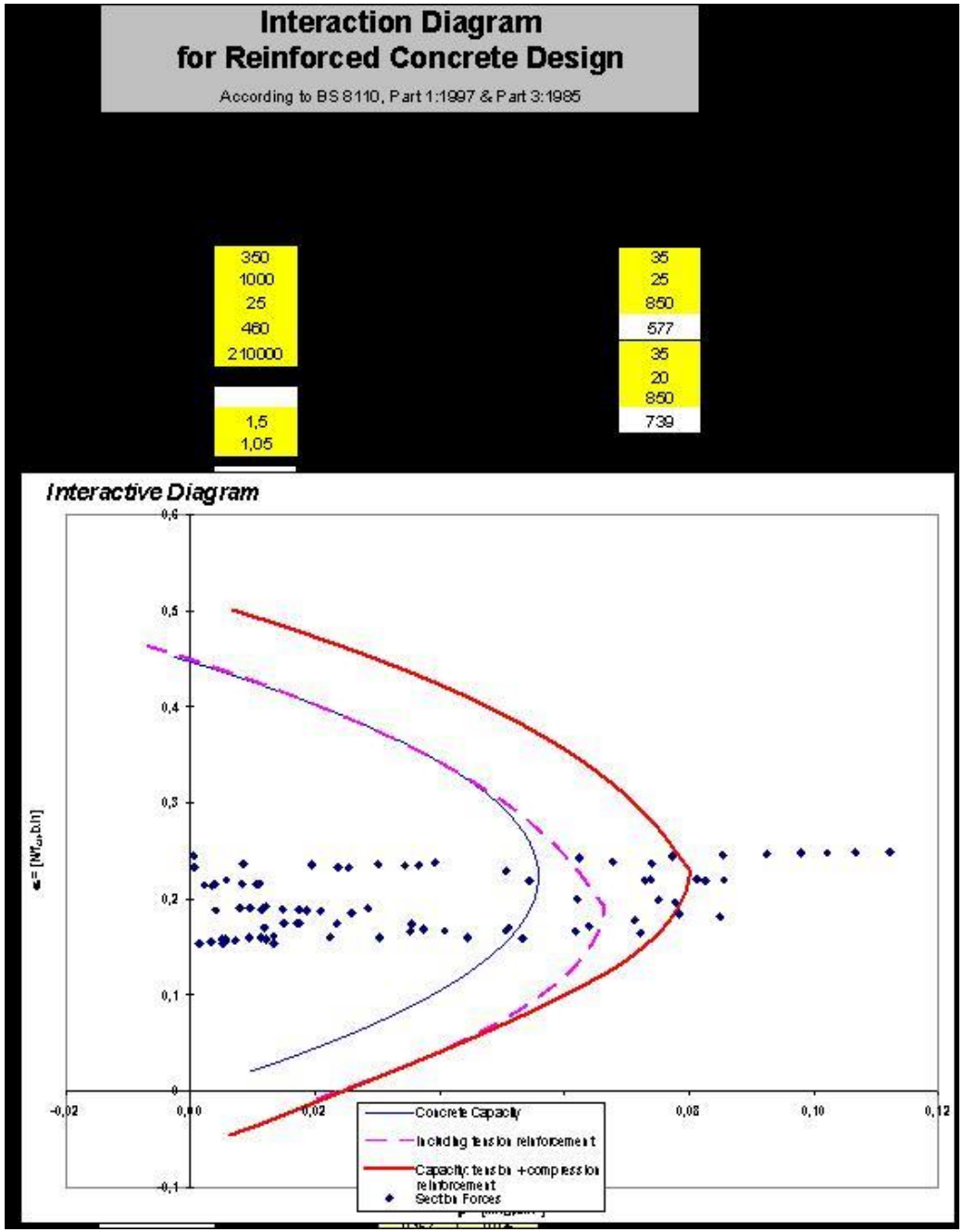
Recognisable maximum deformation of 21 mm.
Heavy loading of support is (of course) modelled.



Axial forces (blue ‘fence’) and bending moments (red ‘fence’). Deformation ‘only’ 26 mm, *until ‘plastic hinges’ were softened.*

(‘Elephant-footing’ failure also commencing)



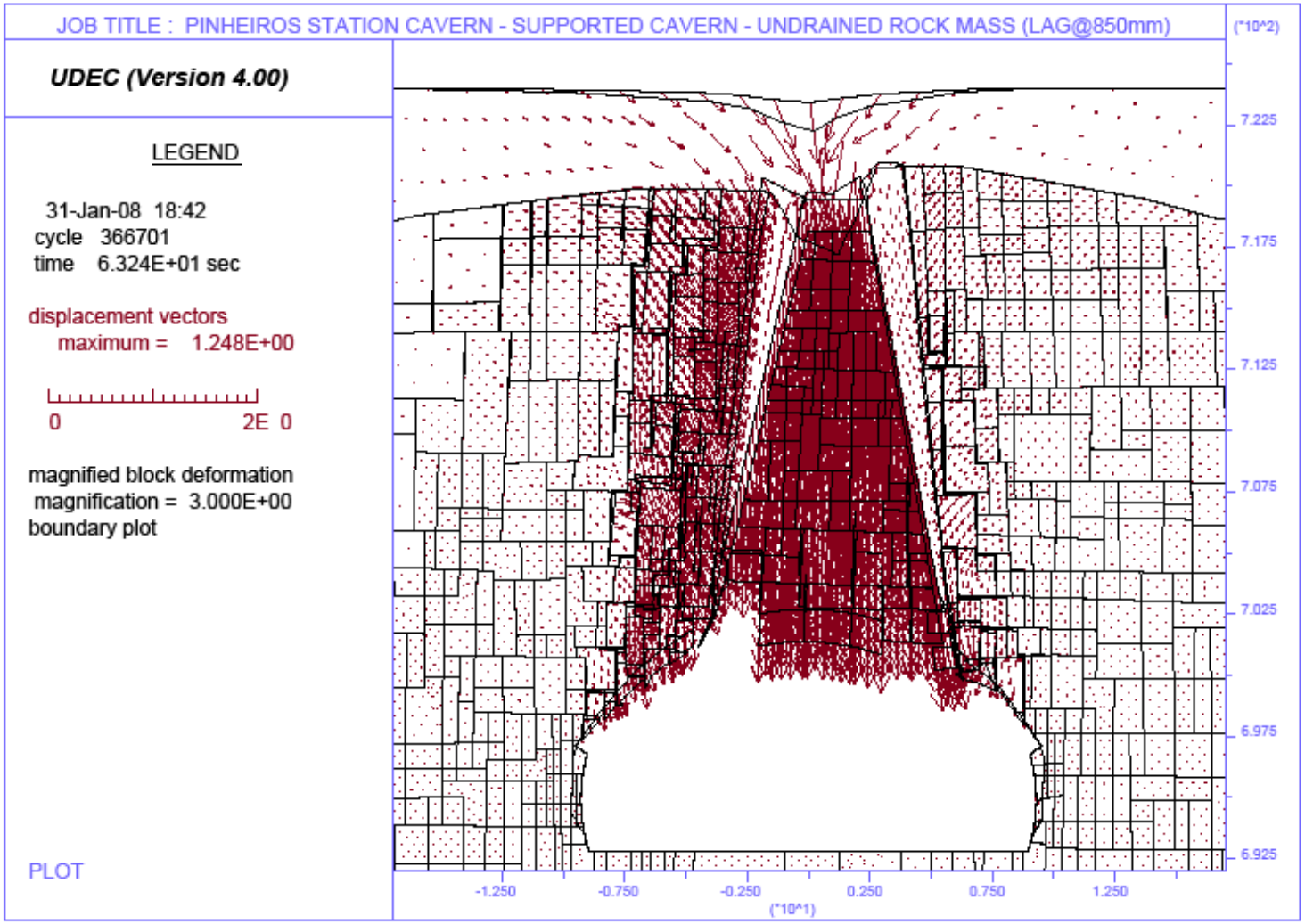


'N-M interaction' diagram.

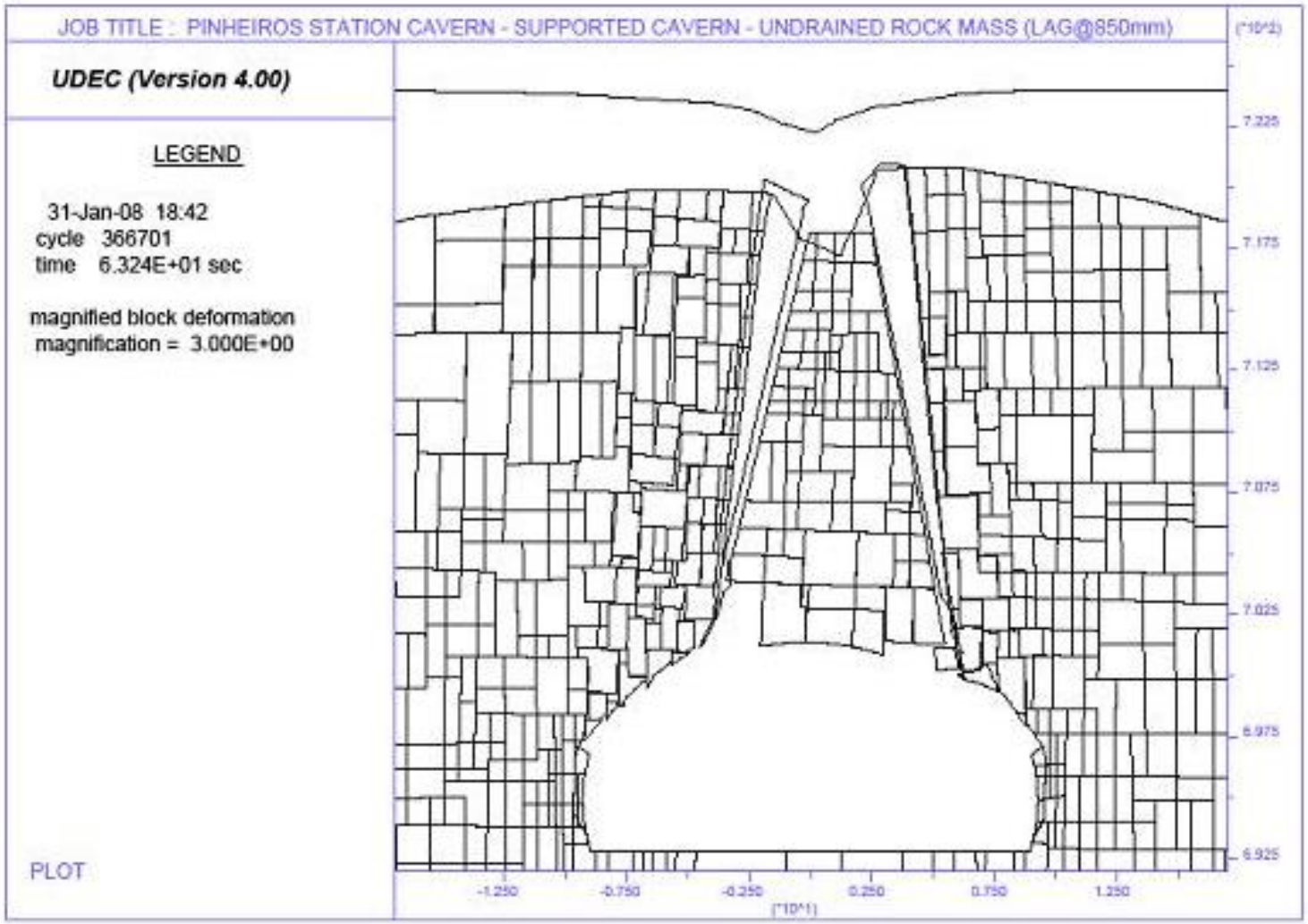
Points beyond the red curve are treated as 'plastic hinges' and are softened.

General failure commences.

Ultimate failure of support: deformation vectors



This ‘block diagram’ now shows loss of contact on left of ridge



Finally – the assumed triggering mechanism

- Water and *water pressure* from cracked pipe
- Located at rear discontinuity, beneath R. Capri
- Exceptionally heavy rains 3-4 weeks before

700 mm diameter sewage pipe – presumed cracked by down-dip shearing, when the cavern arch approached and passed 20 m below this ***planar discontinuity.***

Jr = 1.0 to 1.5

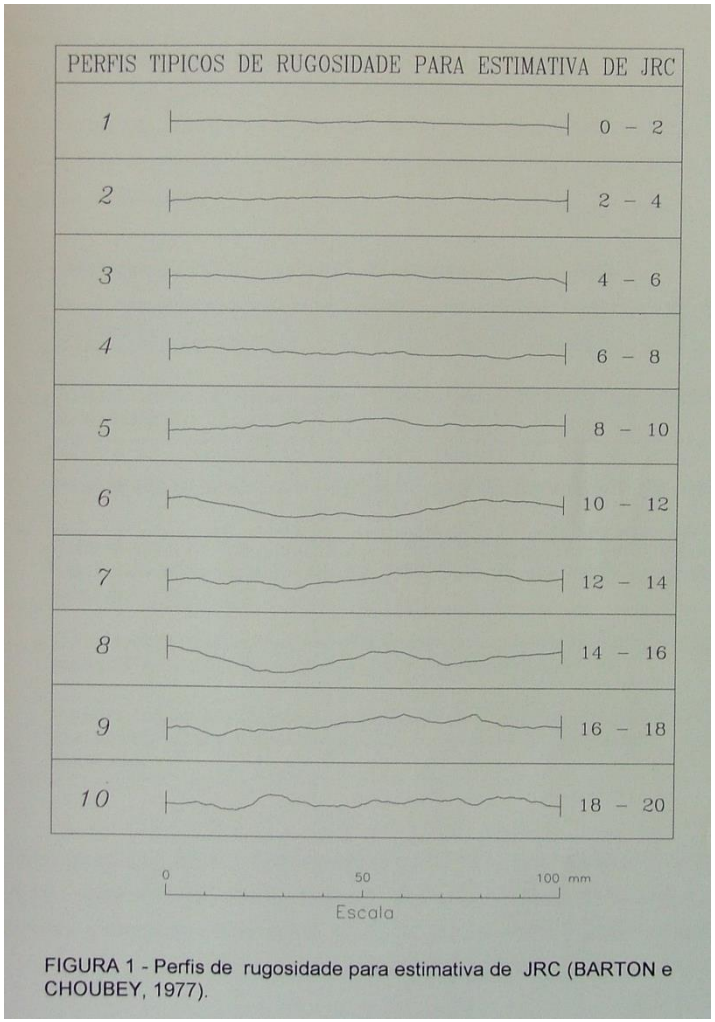
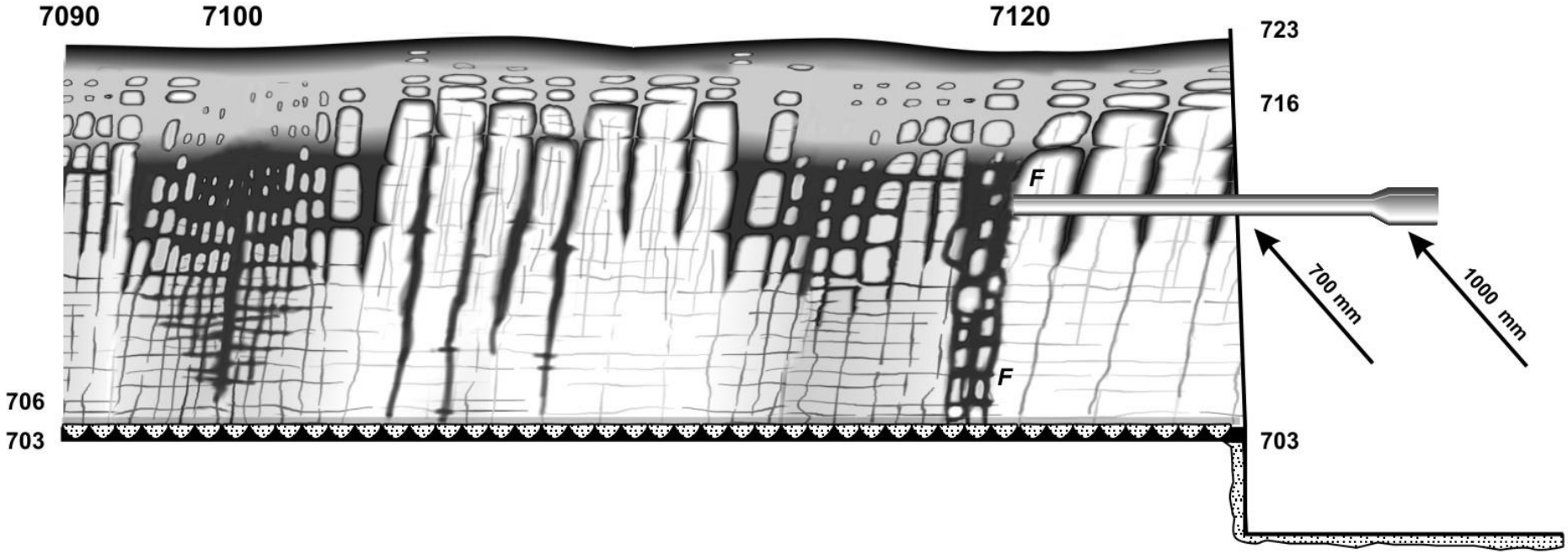
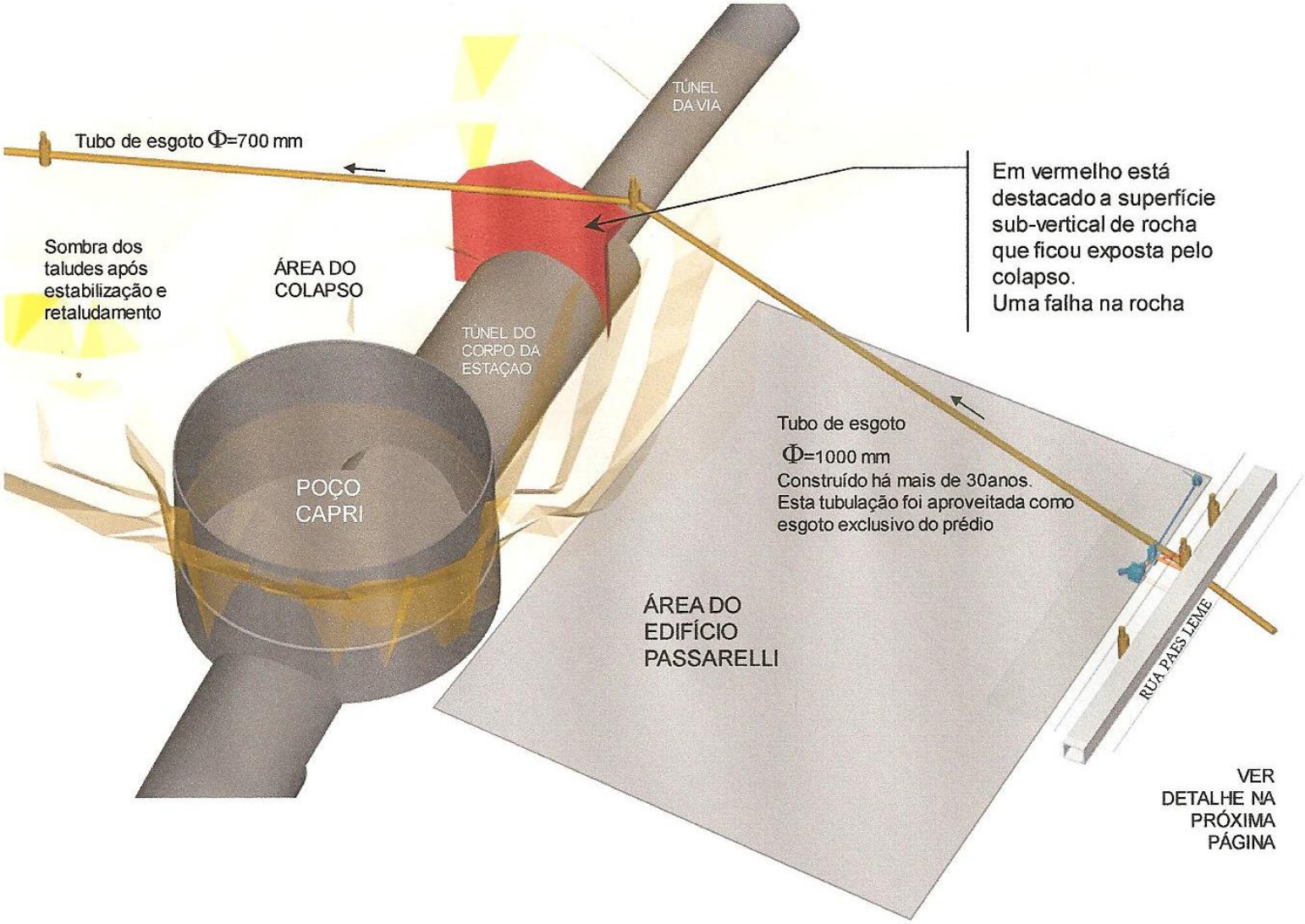


FIGURA 1 - Perfis de rugosidade para estimativa de JRC (BARTON e CHOUBEY, 1977).

The fractured pipe that may have supplied the various adverse geological structures with water and water under pressure. (We now know that 'FF' was not a fault, just a major discontinuity)



The storm drain that fate determined should cross the major geological discontinuity surface (red).



RECOMMENDATIONS (are obvious)

1. Deeper construction from the underground, as practiced of necessity in many cities lacking suitable geology, could be a future, cheaper, and safer solution (for São Paulo), and would also result in less settlement damage.
2. Rock conditions for tunnelling are invariably more favourable at depth, whereas the 'near-surface' is more unpredictable due to the effects of deep differential weathering and locally reduced rock quality.

Go deeper!