L2 Metro Lima: **TBM excavation design (Settlement – PAT) & construction follow up**

ETH – Zurich,
December 2022

Lombardi

Agenda

1. Overview L2 Metro Lima
2. Geotechnical context
3. Settlements & pressures definition
4. Soil conditioning
5. Construction follow up

Overview

Metro Lima
General Layout

Legend:

Line 1: operating
Line 2: under construction
Line 3: design stage
Line 4: design stage
Line 5: under evaluation
Line 6: under evaluation

General information of the Line 2:

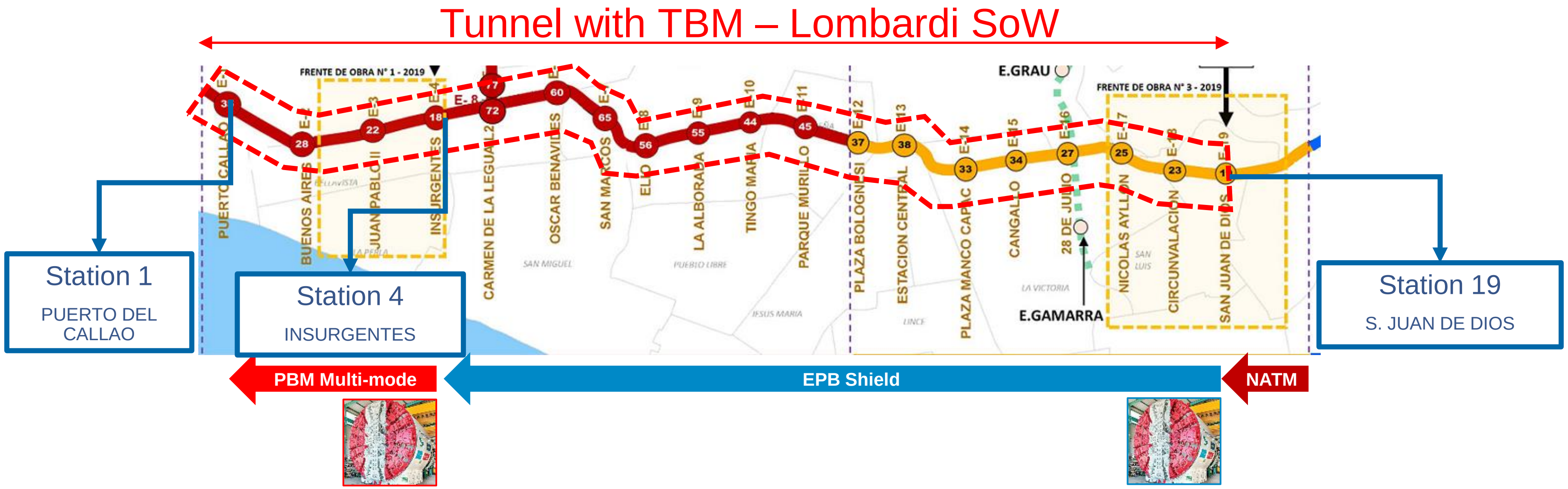
_First underground fully automated metro in Peru' (Vmax = 90km/h)

_ ~ 660'000 passengers per day

_Total cost > $ 3 Billion

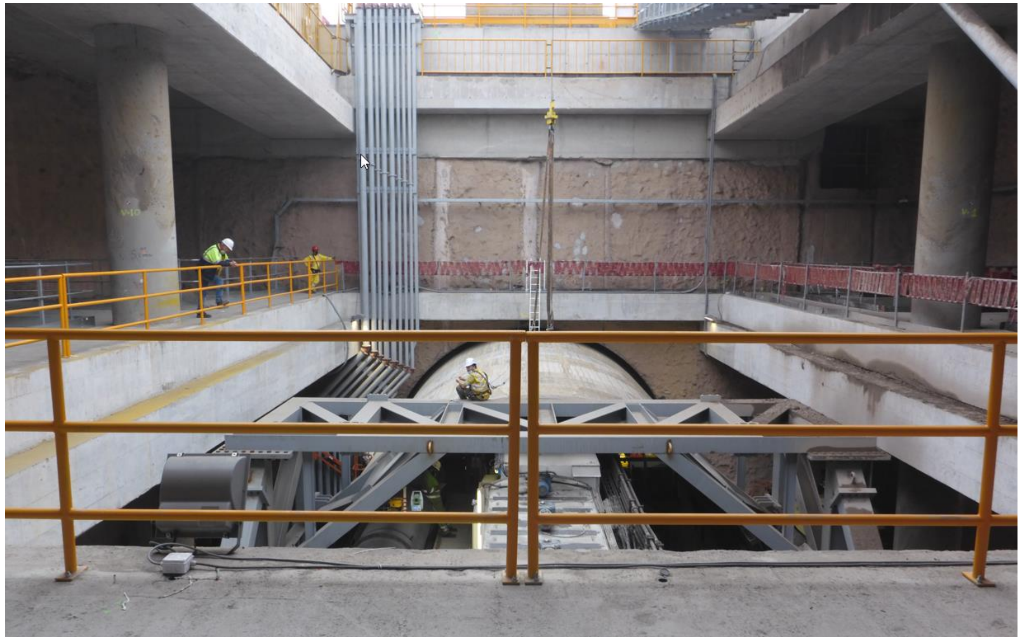
_Main benefit → Environmental sustainability (strong reduction of vehicular traffic)

Metro Lima
Line 2 – TBM section

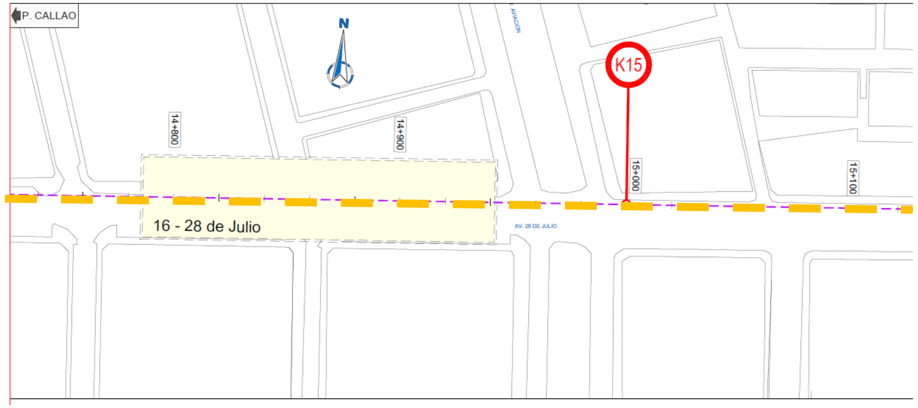


Key facts (Line 2, TBM section):

- 17.3km of mechanized excavation
- 1 TBM - EPB Shield
- 1 TBM - Multi-mode (EPB / Slurry)
- Excavation diameter Φ_{exc} = ~10.3 m
- Max. Overburden = 19.5 m
- Min. Overburden = 4.5 m
- 19 Stations + 18 Ventilation shafts



Metro Lima
Line 2 - Urban context



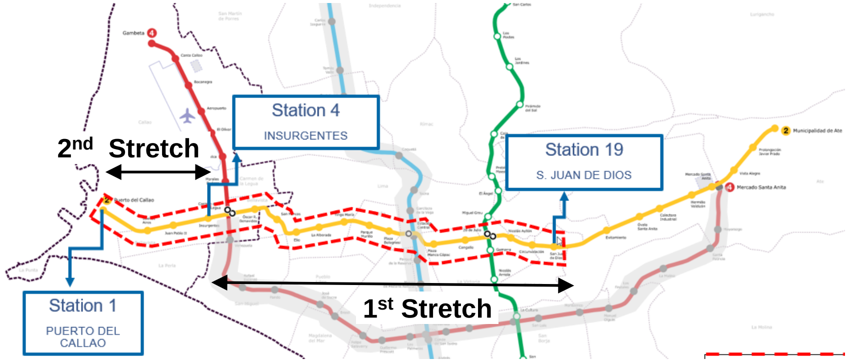
Alignment in a high-density urban area, under the road

Lima Geotechnical context

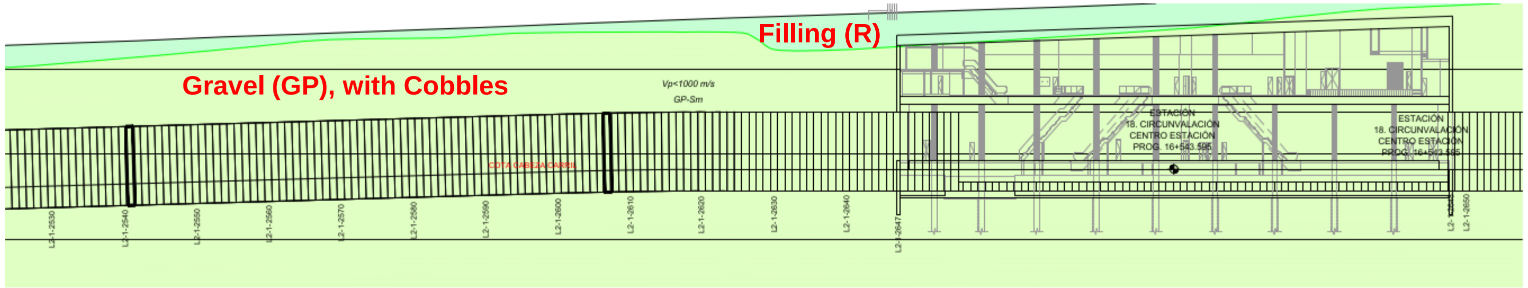
Geotechnical context

Geological conditions

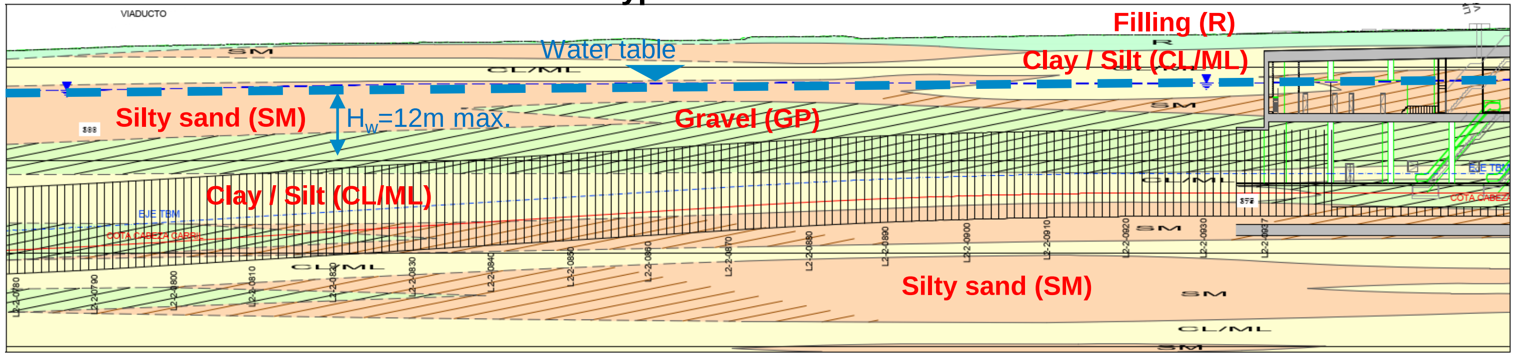
R	Anthropic fill
	Alluvial deposit:
CL/ML	Clay / Silt
SM	Silty sand
GP	Gravel poorly graded



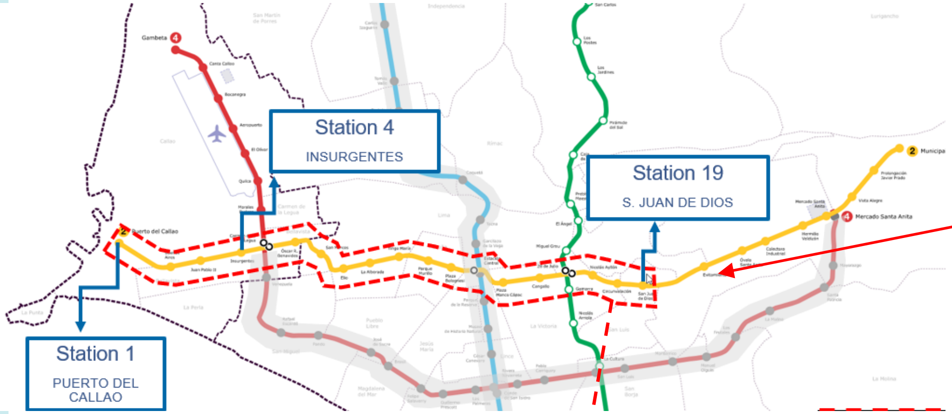
1st Stretch - Typical condition from ST19 to ST4



2nd Stretch - Typical condition from ST4 to ST1



Geotechnical context
Excavation face



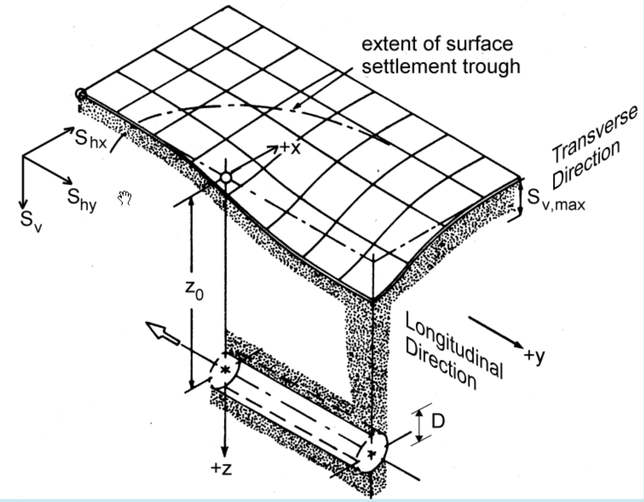
Face condition NATM

Face condition TBM tunnel

Soil condition after TBM excavation

Settlements & pressures definition and building damage estimation

Methodology

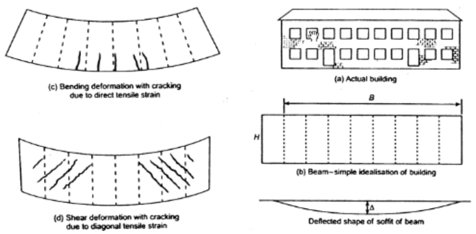


1) First stage preliminary: analytical assessment FF

Sv< 10 mm
Δ/L(mm/m)<1/500
Yes

_ **Green field settlement estimation**
(*Peck, 1969; O'Reilly and New, 1982; Attewel & Woodman, 1982; Moh & Hwang, 1996, Burland & Wroth, 1974*)

No

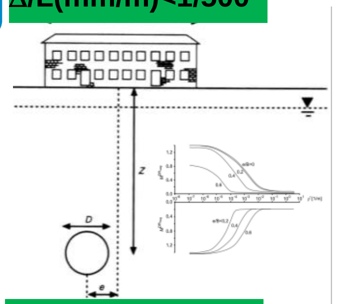


2) Second stage: analytical assessment simplified interaction

εmax
Δ/L(mm/m)<1/500
Yes

_ **Building deflection and horizontal strain considering building stiffness**
(*Potts & Addenbrooke, 1997*)

No



3) Third stage: detailed evaluation

εmax
Δ/L(mm/m)<1/500
Yes

_ **Building deflection and horizontal strain by numerical calculations**

No

Negligible to slight damage

Protective measures

Volume loss definition

The ratio of the volume of the surface settlement trough to the excavated face area usually expressed as percentage.

Volume loss procedure definition

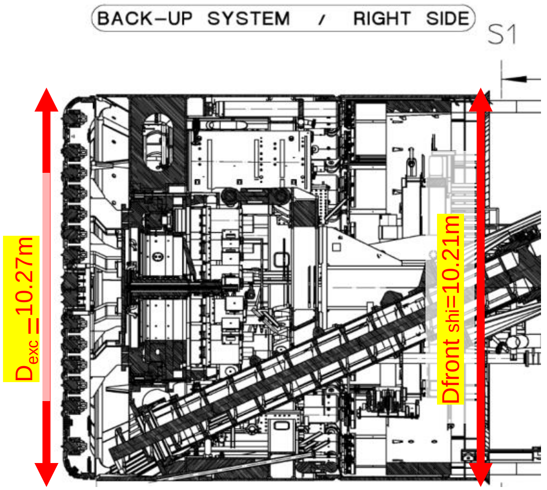
_ 1 Geometrical volume loss: difference between excavation diameter and tail shield diameter (conicity of shield).

_ 2 Evaluation of efficiency: according to N. Ruse & H. Schwarz graph

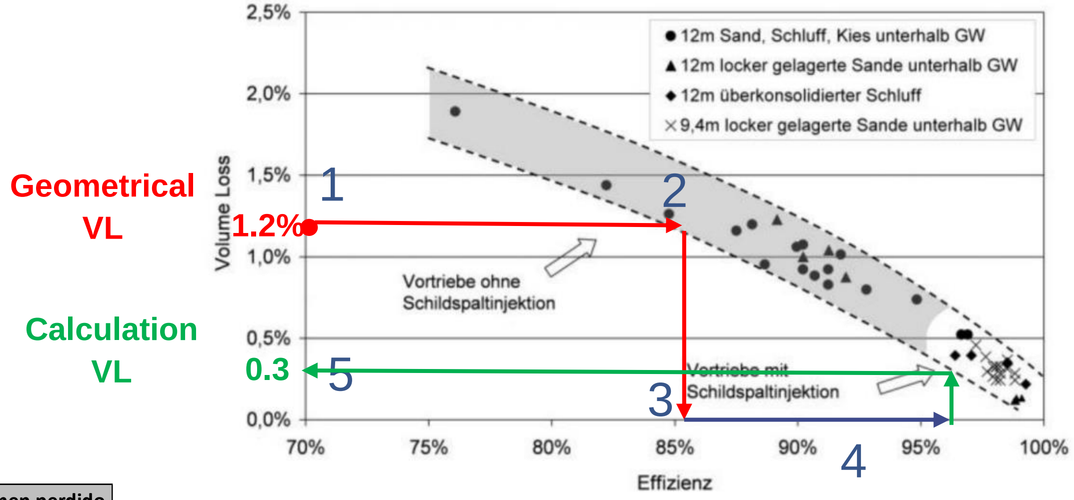
_ 3 Risk analysis: evaluation of the key factor can generate volume loss (face pressure, grout pressure, weight of excavated material, grout volume injection…) and definition of the mitigation measures (excavation control, topographic control , quality system for excavation procedure…)

_ 4 Evaluation of the increment on the efficiency of the excavation through a risk analysis

_ 5 Definition of Volume loss for calculation

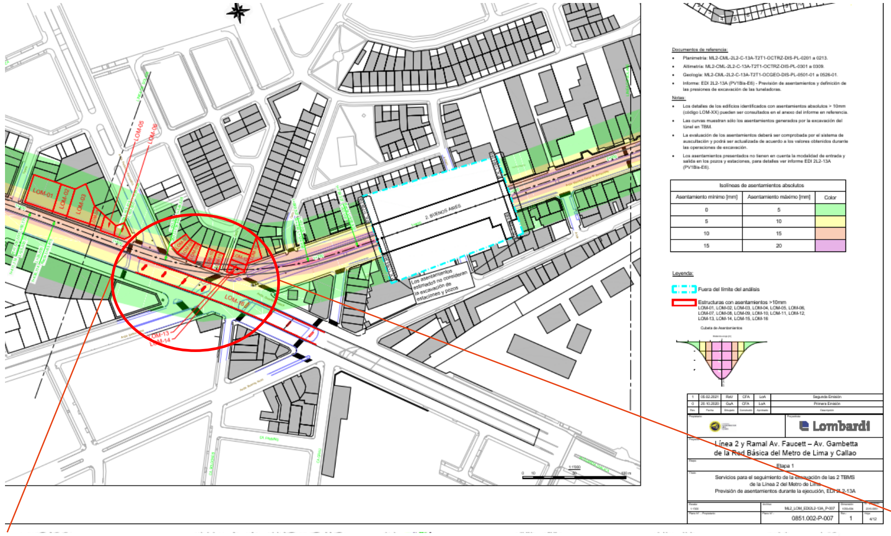


N. Ruse & H. Schwarz (2012)



Sección	Diámetro	Área [m²]	% respecto al área de excavación	% volumen perdido
Excavación	10.27	82.84	100	0
Escudo delantero	10.21	81.87	98.8	1.2

Analytical assessment: results of settlement evaluation and damage estimation



Settlements

Isolíneas de asentamientos absolutos		
Asentamiento mínimo [mm]	Asentamiento máximo [mm]	Color
0	5	(verde)
5	10	(amarillo)
10	15	(naranja)
15	20	(rosa)

Admissible level of deformation

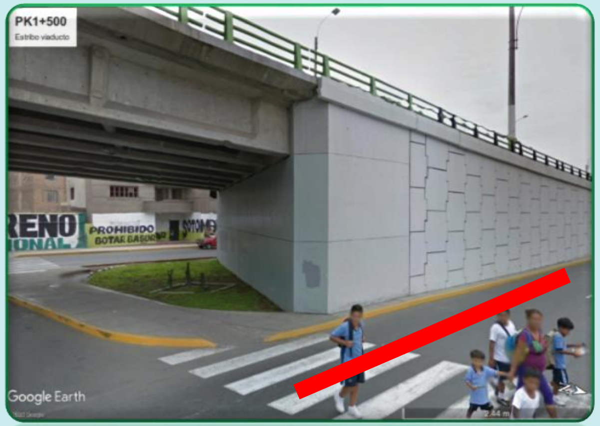
Categoría de daño	Índice de vulnerabilidad de la estructura, I_v				
	Despreciable	Bajo	Ligero	Moderado	Alto
	$0<I_v<20$	$20<I_v<40$	$40<I_v<60$	$60<I_v<80$	$80<I_v<100$
	Factor de reducción, F_R				
	$F_R=1.0$	$F_R=1.25$	$F_R=1.5$	$F_R=1.75$	$F_R=2.0$
	Deformación límite por tracción, ε_{lim} [%]				
0	$\varepsilon_{lim}<0.05$	$\varepsilon_{lim}<0.04$	$\varepsilon_{lim}<0.033$	$\varepsilon_{lim}<0.029$	$\varepsilon_{lim}<0.025$
1	$0.05<\varepsilon_{lim}<0.075$	$0.04<\varepsilon_{lim}<0.06$	$0.033<\varepsilon_{lim}<0.05$	$0.029<\varepsilon_{lim}<0.043$	$0.025<\varepsilon_{lim}<0.038$
2	$0.075<\varepsilon_{lim}<0.15$	$0.06<\varepsilon_{lim}<0.12$	$0.05<\varepsilon_{lim}<0.1$	$0.043<\varepsilon_{lim}<0.086$	$0.038<\varepsilon_{lim}<0.075$
3	$0.15<\varepsilon_{lim}<0.3$	$0.12<\varepsilon_{lim}<0.24$	$0.1<\varepsilon_{lim}<0.2$	$0.086<\varepsilon_{lim}<0.171$	$0.075<\varepsilon_{lim}<0.15$
4 y 5	$0.3<\varepsilon_{lim}$	$0.24<\varepsilon_{lim}$	$0.2<\varepsilon_{lim}$	$0.171<\varepsilon_{lim}$	$0.15<\varepsilon_{lim}$

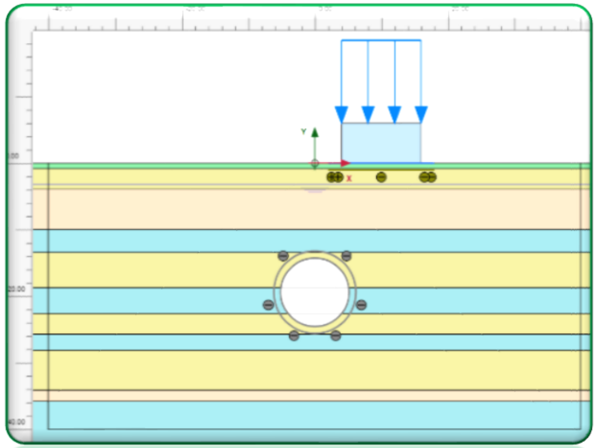
Damage category

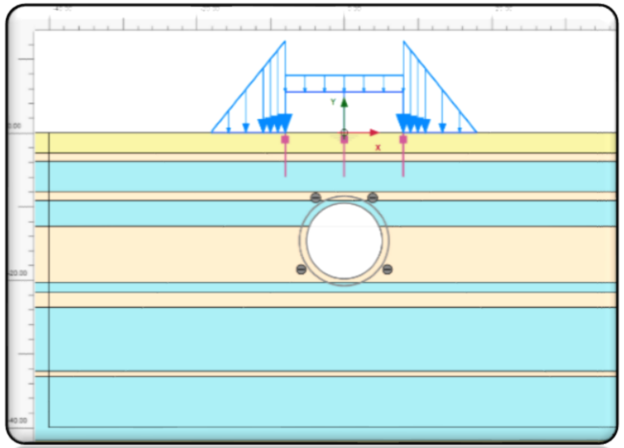
Índice vulnerabilidad [-]	ε_{max} [%]	Categoría de daño
0-20	0.07	1
20-40	0.06	2
20-40	0.06	2
20-40	0.11	2

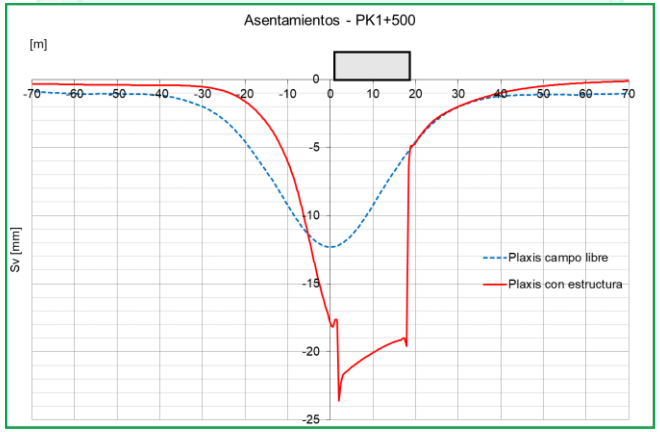
Numerical Models

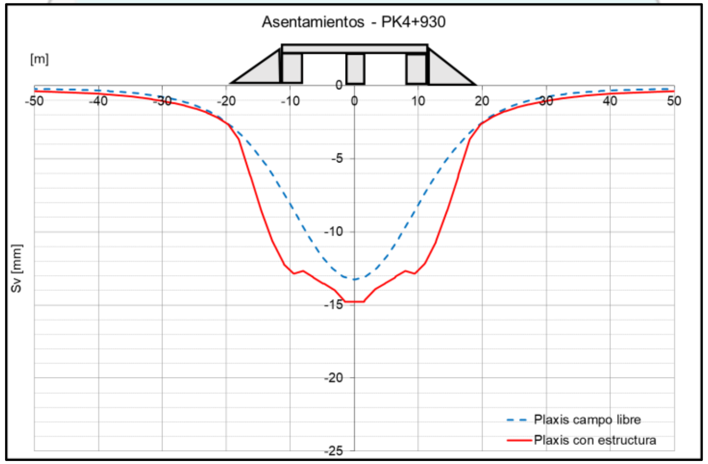
PK	Estructura	Δ/L [mm/m]	ε_h [%]
1+500-1+600	Puente Chalaca	0.22	0.21
4+930	Puente Carmen de la Legua	0.29	0.10







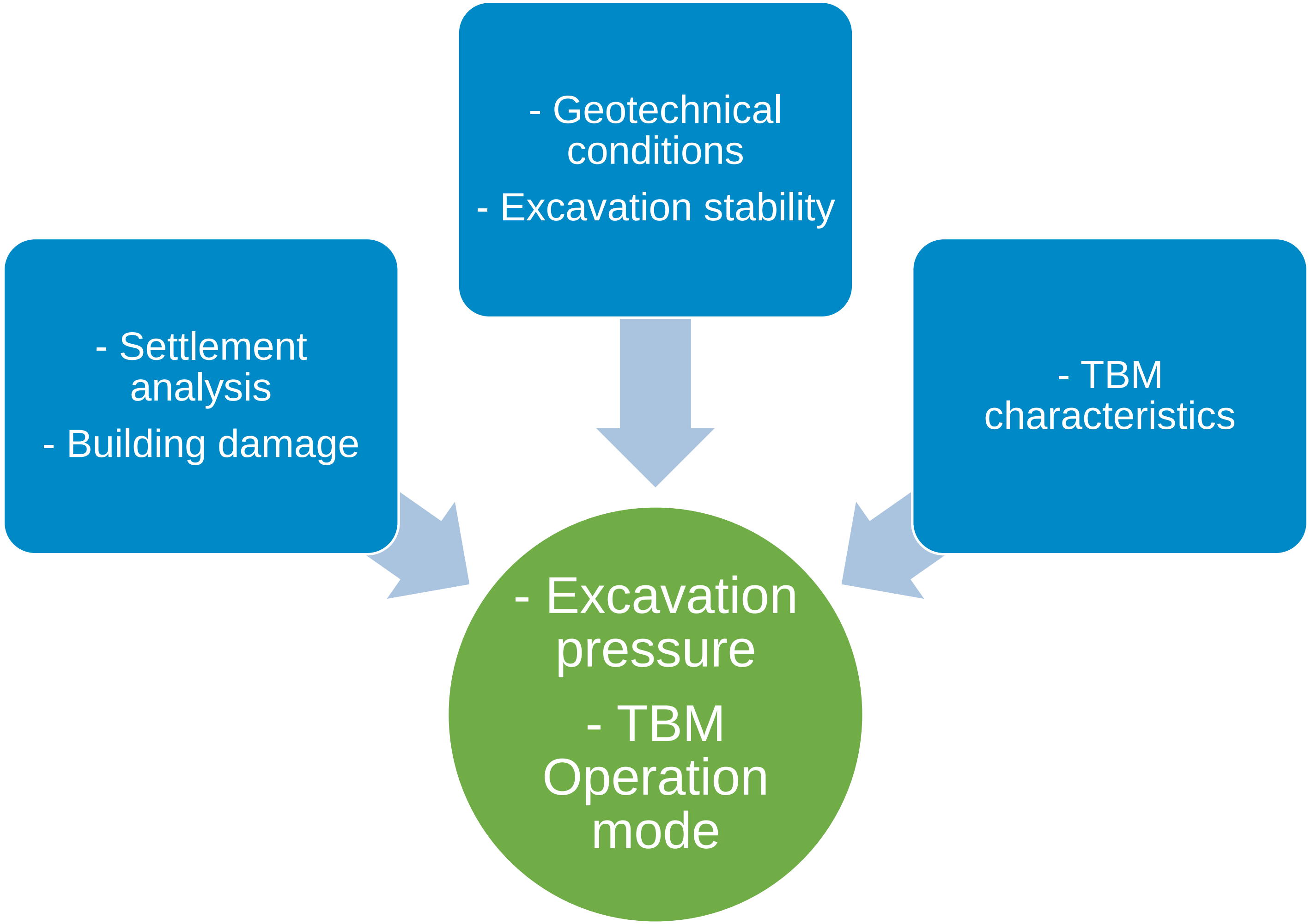




Modelo	$S_{v,max}$ [mm]	ε_h [%]	β_{max} [mm/m]	Categoría de daño
Plaxis campo libre	12	0.05	0.5	2, Ligero
Plaxis con estructura	24	0.01	0.2	0, Despreciable

Modelo	$S_{v,max}$ [mm]	ε_h [%]	β_{max} [mm/m]	Categoría de daño
Plaxis campo libre	13	0.075	0.4	2, Ligero
Plaxis con estructura	15	0.035	0.3	1, Muy ligero

Excavation pressures: How to define it?



Results of the calculation

Caquot & Kerisel (1956)

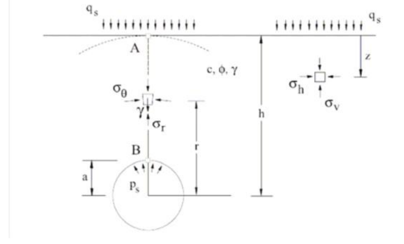


Figura 26: Modelo de Caquot y Kerisel [23].

Anagnostou & Kovari (1994, 1996)

Anagnoustou y Kovari proponen el siguiente mecanismo de ruptura según Horn (1961):

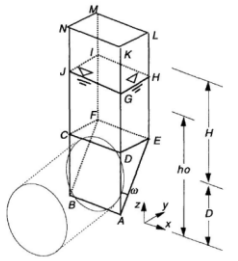


Figura 25: Mecanismo de ruptura del frente propuesto por Anagnostou y Kovari (1994, 1996).

DAUB (2016)

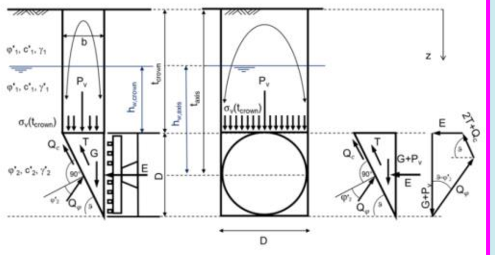
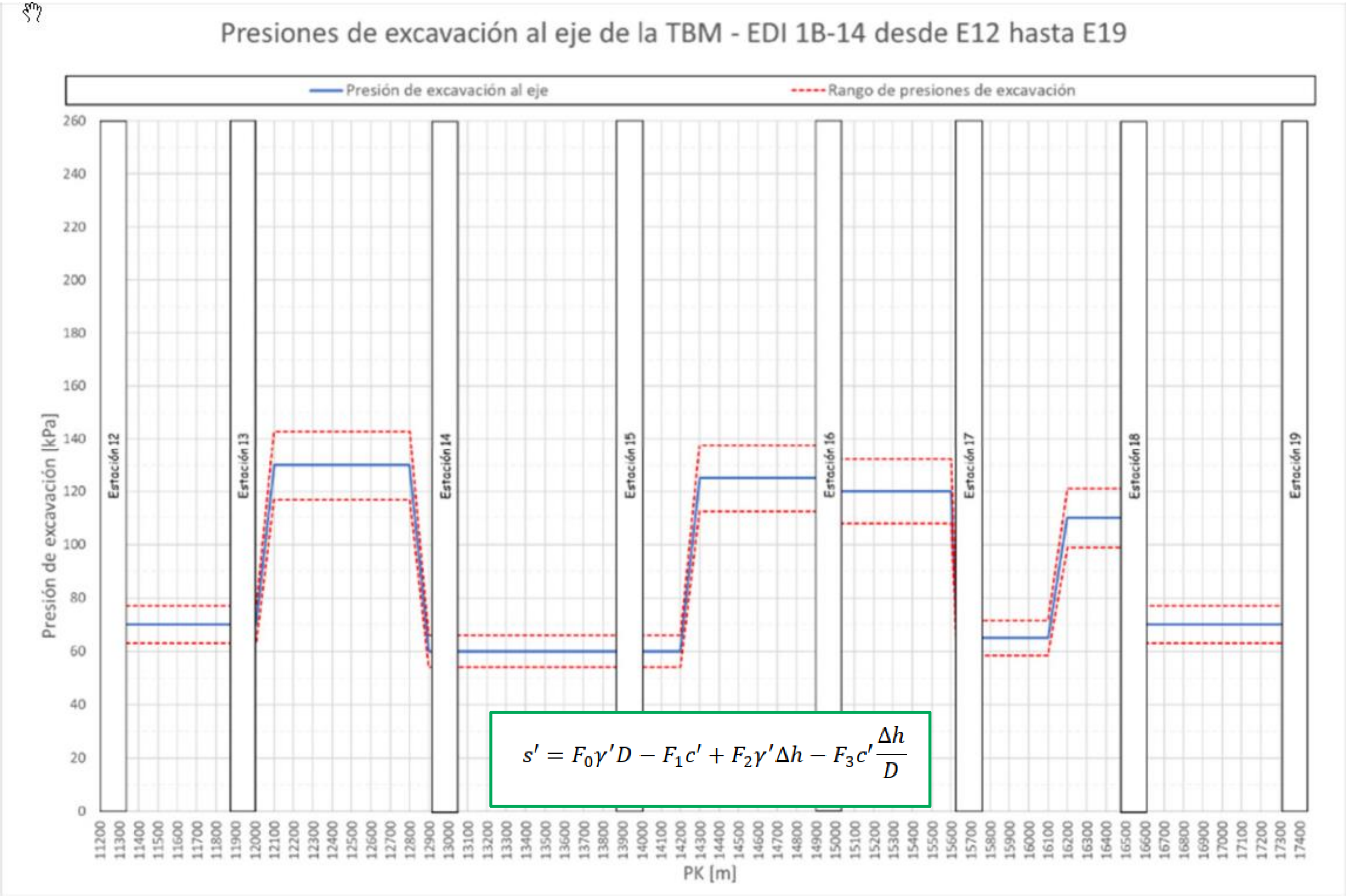
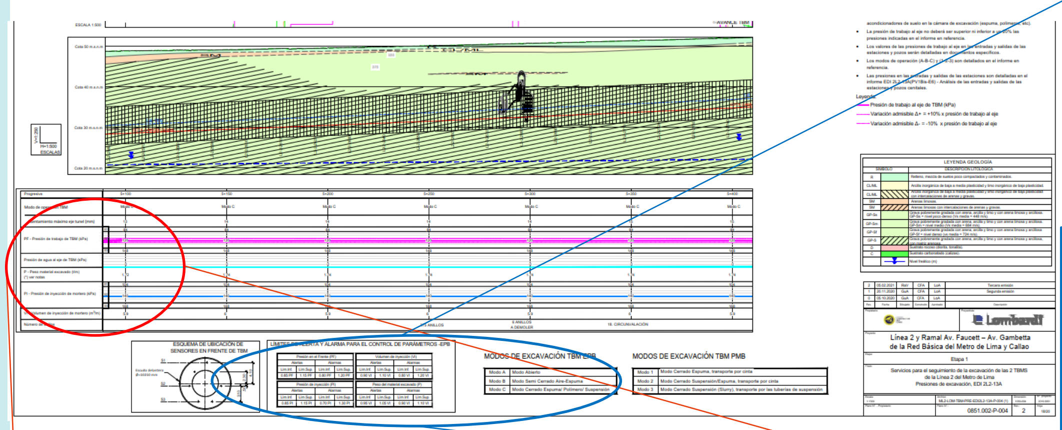


Figura 27: Equilibrio de fuerzas que actúan en el bloque de deslizamiento del frente [27].



$$s' = F_0\gamma' D - F_1 c' + F_2\gamma'\Delta h - F_3 c'\frac{\Delta h}{D}$$

Results of the calculation: PAT (plan for advance of tunnel)



MODOS DE EXCAVACIÓN TBM EPB

Modo A	Modo Abierto
Modo B	Modo Semi Cerrado Aire-Espuma
Modo C	Modo Cerrado Espuma/ Polímero/ Suspensión

LÍMITES DE ALERTA Y ALARMA PARA EL CONTROL DE PARÁMETROS -EPB

Presión en el Frente (PF)			
Alertas		Alarmas	
Lim.Inf.	Lim.Sup.	Lim.Inf.	Lim.Sup.
0.85 PF	1.15 PF	0.80 PF	1.20 PF

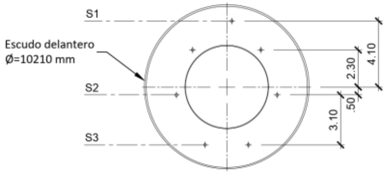
Volumen de inyección (VI)			
Alertas		Alarmas	
Lim.Inf.	Lim.Sup.	Lim.Inf.	Lim.Sup.
0.90 VI	1.10 VI	0.80 VI	1.20 VI

Presión de inyección (PI)			
Alertas		Alarmas	
Lim.Inf.	Lim.Sup.	Lim.Inf.	Lim.Sup.
0.85 PI	1.15 PI	0.70 PI	1.30 PI

Peso del material excavado (P)			
Alertas		Alarmas	
Lim.Inf.	Lim.Sup.	Lim.Inf.	Lim.Sup.
0.95 VI	1.05 VI	0.90 VI	1.10 VI

Progresiva		5+100	5+150	5+200
Modo de operación TBM		Modo C	Modo C	Modo C
Asentamiento máximo eje tunel (mm)		13	14	14
PF - Presión de trabajo de TBM (kPa)	S1	84	84	84
	S2	120	120	120
	S3	148	148	148
Presión de agua al eje de TBM (kPa)		0	0	0
P - Peso material excavado (t/m) (*) ver notas		1.72	1.74	1.74
PI - Presión de inyección de mortero (kPa)	S1	104	104	104
	S2	140	140	140
	S3	168	168	168
VI - Volumen de inyección de mortero (m^3/m)		5.9	6	5.9

ESQUEMA DE UBICACIÓN DE SENSORES EN FRENTE DE TBM



Soil Conditioning for EPB excavation

Soil Conditioning laboratory test

Laboratory test carried out:

_ The half-life time of a foam:

defined as the time required by a foam to drain 50% of the weight of the initial conditioning liquid used in foam generation (EFNARC, 2005)

_ The fall cone test:

measures the penetration hf of a cone dropped under its own weight after being released from the standardized support

_ The pull-out test:

represents a family of widespread systems for measuring the adhesion between a metallic element and the soil.

_ Slump test and flow table test:

the slump test is carried out using the Abrams cone, the flow table test or flow test is a method to determine the consistency of specimens.

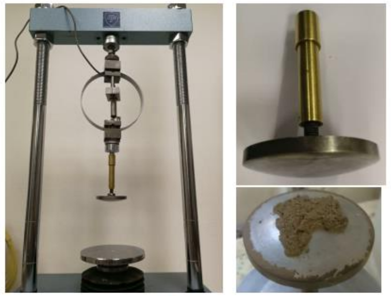


Figure 4. Pull-out plate test laboratory apparatus.

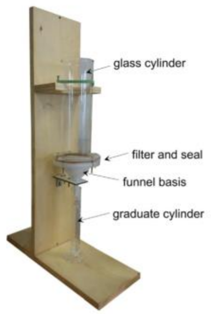
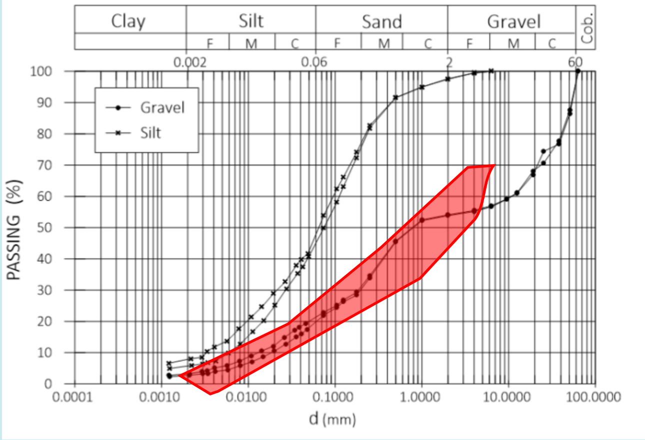


Figure 1. Half-time life test apparatus.

Figure 3. Fall cone test apparatus.

Figure 5. Slump test (left) and flow table test (right) apparatuses.

Soil conditioning Gravel



Startup di

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SAPIENZA UNIVERSITÀ DI ROMA

Table 3: Conditioning parameters and results for the gravel.

Product	ID	w_{add} (%w)	FER (xx:1)	FIR (%)	TR (l/m³)	w_{cond} (%)	Slump (cm)	Abrasiveness (g)
CLB F5/M	SP1	0.00	15.00	20.00	0.27	11.49	15.50	0.11
	SP2	5.00	15.00	30.00	0.40	17.32	16.50	0.10
	SP3	2.50	15.00	30.00	0.40	13.83	11.50	0.08
	SP4	5.00	15.00	20.00	0.27	16.52	10.00	0.14
	SP5	5.00	12.00	25.00	0.42	19.98	10.00	0.14
ACTISOYL 20W	SP6	5.00	15.00	30.00	0.40	20.86	8.50	0.14
	SP7	5.00	15.00	40.00	0.53	20.75	11.50	0.12
	SP8	2.50	15.00	72.50	0.97	17.19	21.50	0.10
	SP9	5.00	15.00	50.00	0.67	16.06	16.50	0.10
	SP10	5.00	12.00	25.00	0.42	20.60	8.00	0.16

Laboratory test results carried out with two foaming agents: CLB F5/M (CONDAT) and ACTISOYL 20W (TNL18)

The samples have been conditioned with different dosages, prepared at a natural water content w_n=10%. The concentration of the foam C_f was set as fixed parameter and equal to 2%. The foam expansion ratio FER was chosen based on the granulometry between 12÷15. The added water w_{add} and foam injection ratio FIR were then adjusted to obtain a good soil paste, according to slump test, flow table test and visual inspection. Starting from those parameters, the treatment ratio TR was calculated.

FER: foam expansion ratio. Ratio between the volume of the foam and the volume of foaming solution used.

FIR: foam injection ratio. Ratio between the volume of foam injected and the volume of soil.

C_f: concentration factor of the foam. Percentage ratio between the weight of the foaming agent and the total weight of the foaming solution.

TR: treatment ratio. Volume of foaming agent used to treat a unit volume of soil.

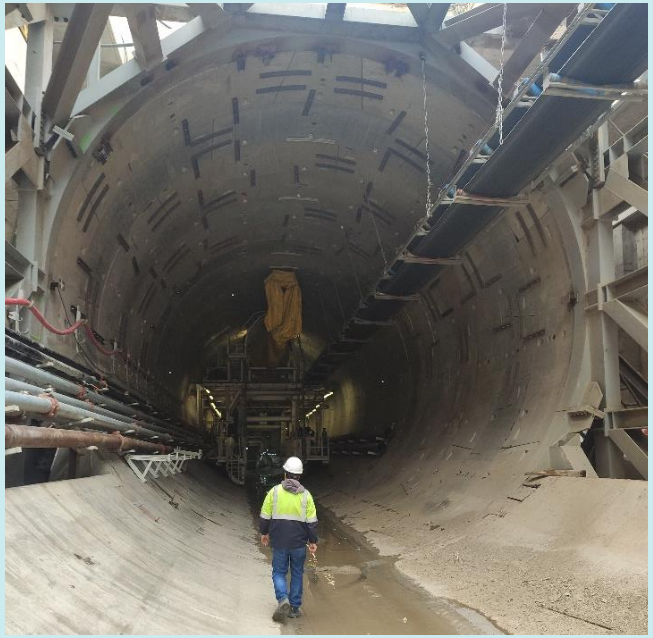
w_n: initial water content of the soil.

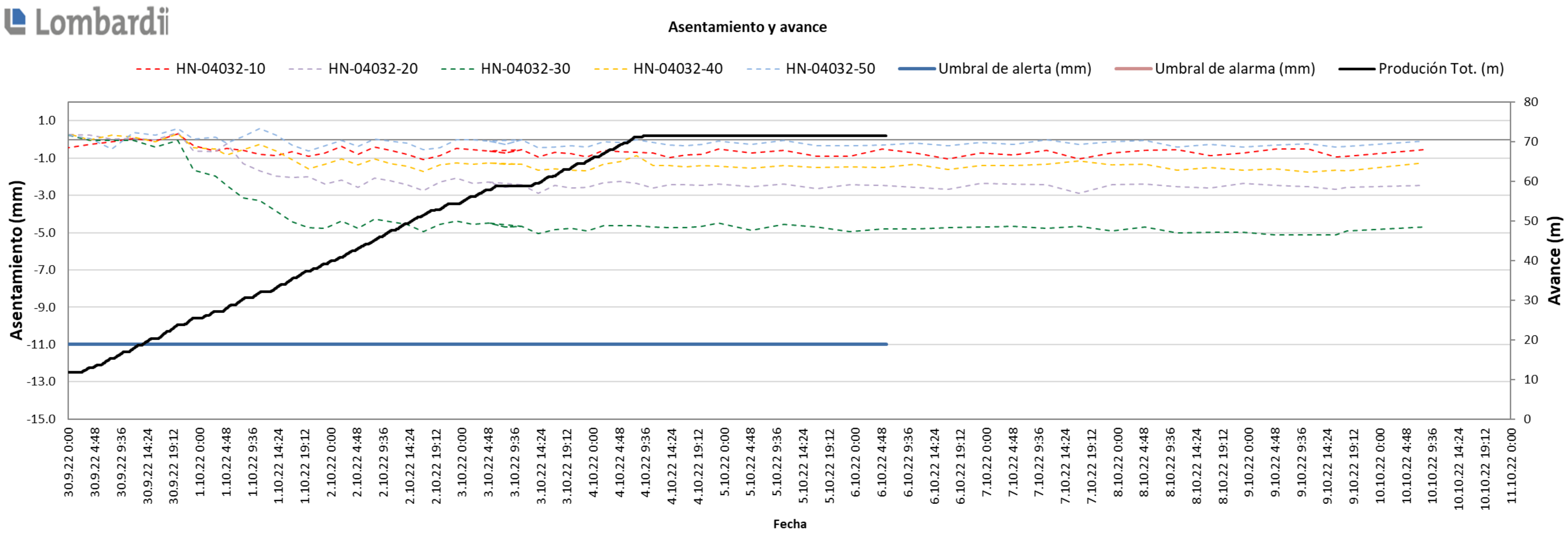
w_{add}: amount of water added for conditioning (% on the weight of the soil).

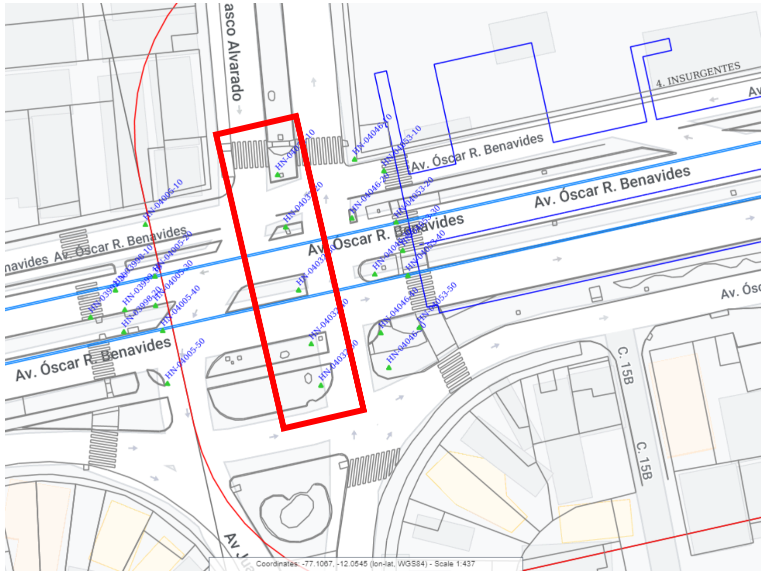
w_{cond}: water content of the conditioned soil

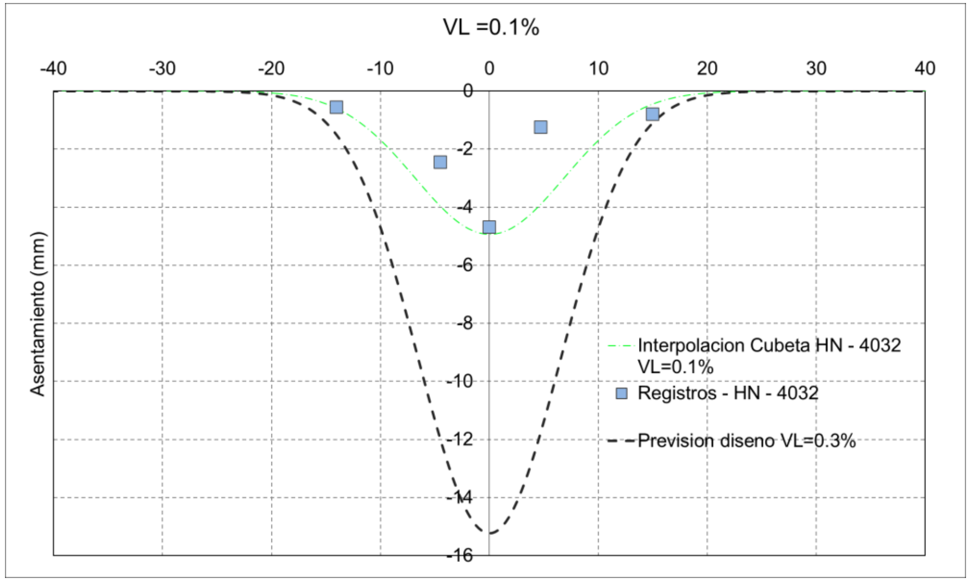
Excavation parameters control

Settlements control

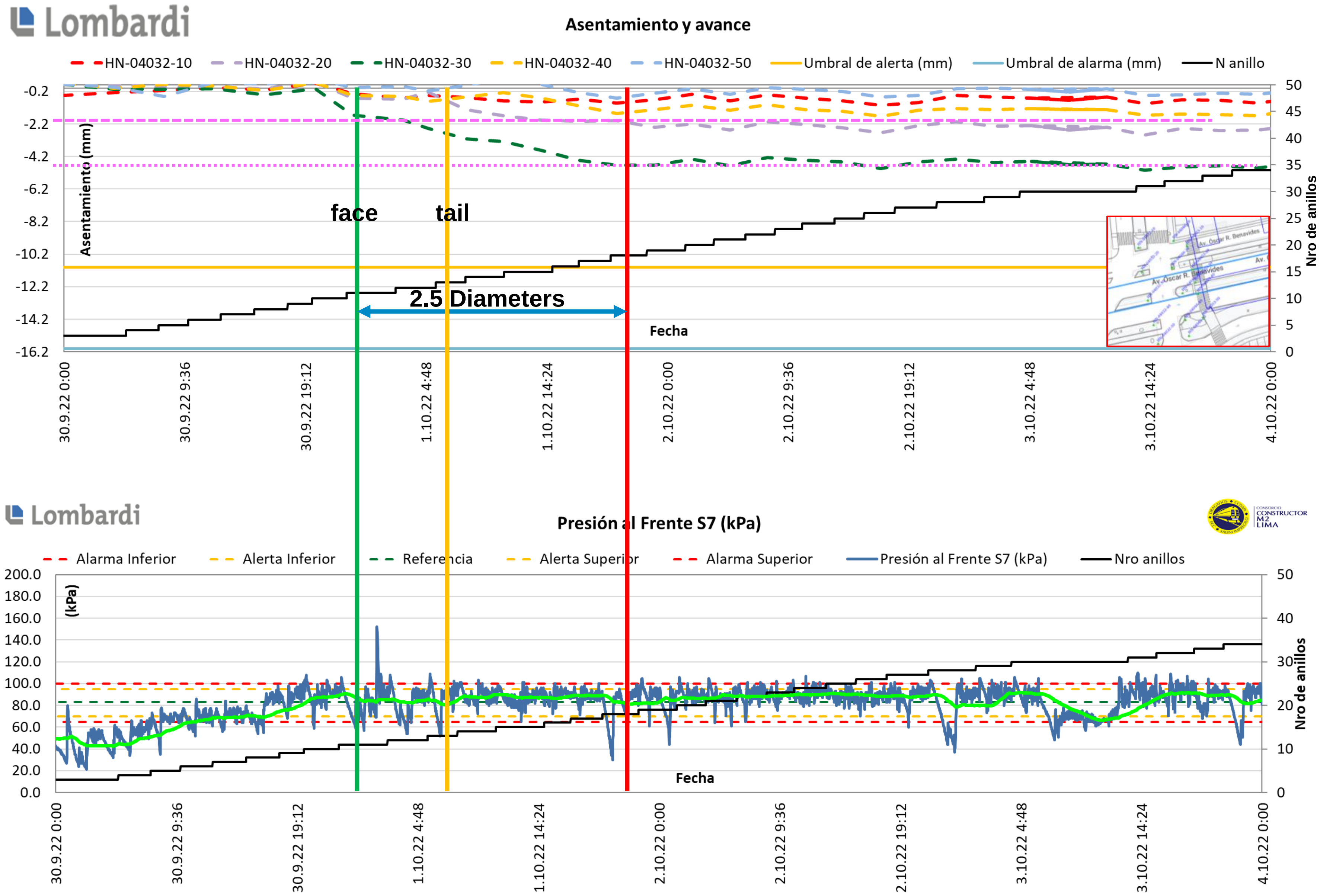








TBM excavation control
(face pressure – tail void injection and volume pressure – weight of excavated material)



Conclusion

_Definition of settlements and excavation pressures is an iterative process (with a continuous control and update)

_With a correct definition of the soil conditioning is possible to achieve the requested:

- **_stability of the face**
- **_level of settlements (with a mitigation of the risk of damage)**
- **_rate of the advance of tunnel excavation**

_The strict control and continuous analysis of excavation and monitoring data are necessary to ensure that TBM advancement takes place with the requested level of safety

_After approx. 2.5 km of excavation of TBM 1 and 1km of excavation of TBM2 the settlements assessment has been respected using the face pressure and other machine parameters defined in the design stage

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Thank you for your attention

Lombardi