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Innovative Engineering Solutions to Geotechnical and Hydrogeological Challenges in Lot 1 of the Pajares Tunnels on the León-Asturias HSR Line in Spain

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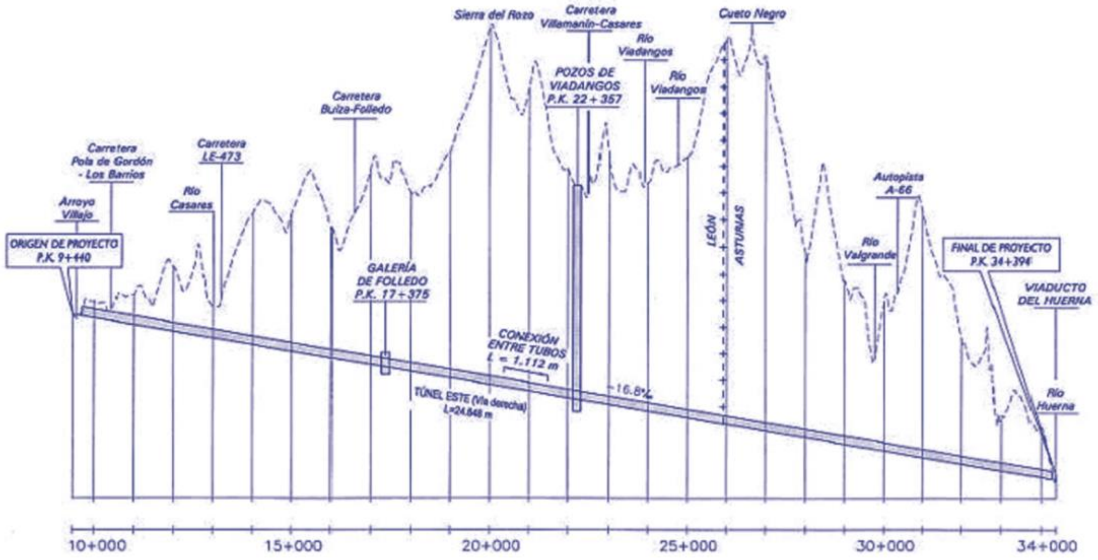
THE PAJARES TUNNELS

The Pajares Base Tunnels are part of the León–Asturias High-Speed Railway



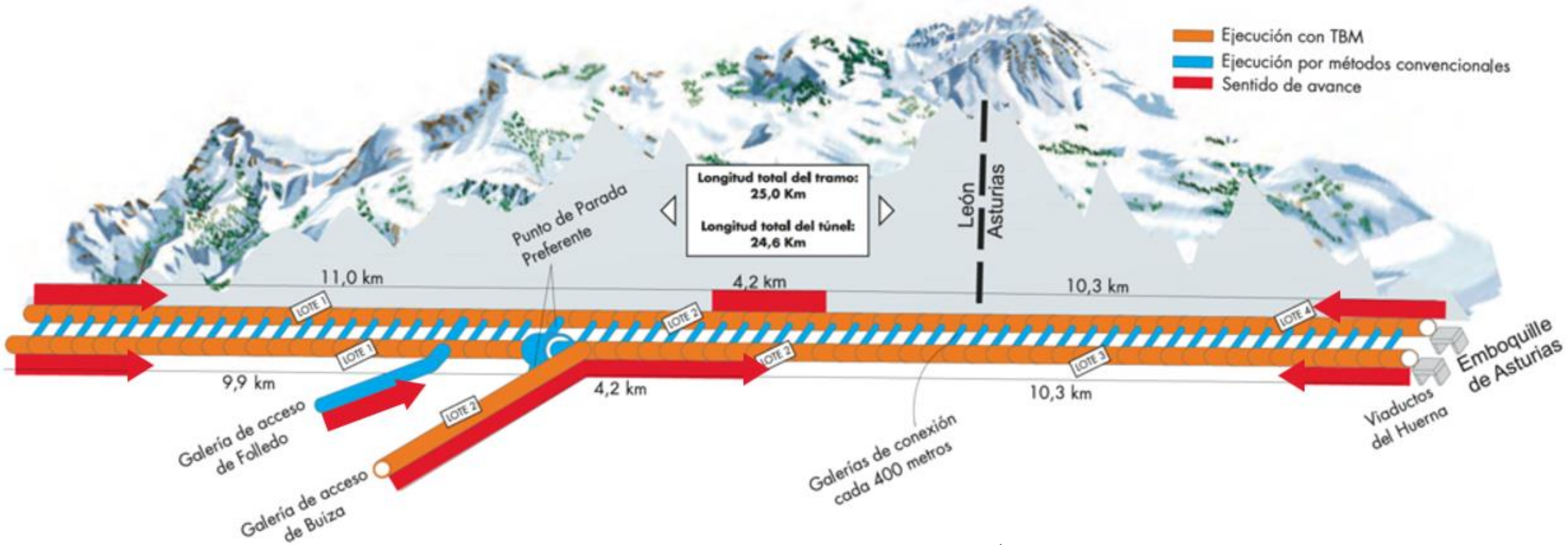
OBJECTIVES

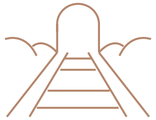
- Eliminate the historical bottleneck of the Pajares mountain pass.
- Replace the obsolete 19th-century single-track alignment (steep gradients, 85 tunnels totalling 28 km).
- Enable operating speeds above 250 km/h.

BENEFITS

- Reduction of travel time.
- Increased freight capacity.
- Improved connection between northern Spain and central Spain.

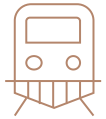
THE PAJARES TUNNELS





KEY FUNCTIONAL FACTS

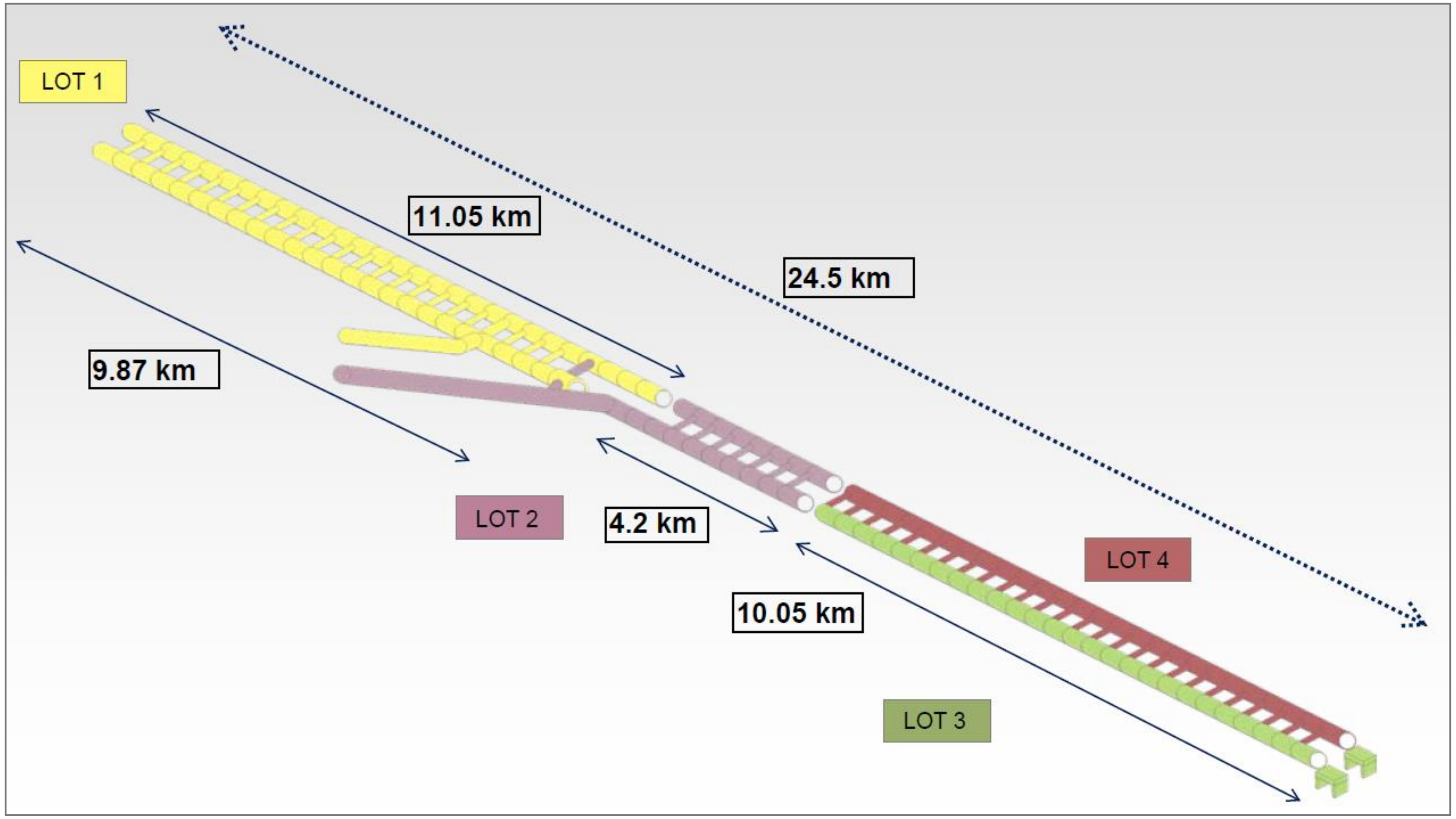
- Designed as a base tunnel to eliminate the steep gradients of the historic Pajares mountain alignment.
- Key rankings:
  - **Second-longest** high-speed rail tunnels in **Spain**.
  - **Sixth-longest** railway tunnels in **Europe**.
  - **Seventh-longest** railway tunnels in the **world** at the time of construction.
- Approx. 80% of the railway alignment runs underground.
- Design speed: **>250 km/h**.



KEY TECHNICAL FACTS

- Two parallel single-track tunnels.
- **24.6 km** long each.
- **8.50 m** internal diameter (TBM-excavated sections).
- **16.8 ‰** longitudinal gradient along the main tunnel alignment.
- Excavated under extreme **overburden** exceeding **1,000 m** in several sections.
- Built through one of the most geologically complex rock masses in Spain.

THE PAJARES TUNNELS



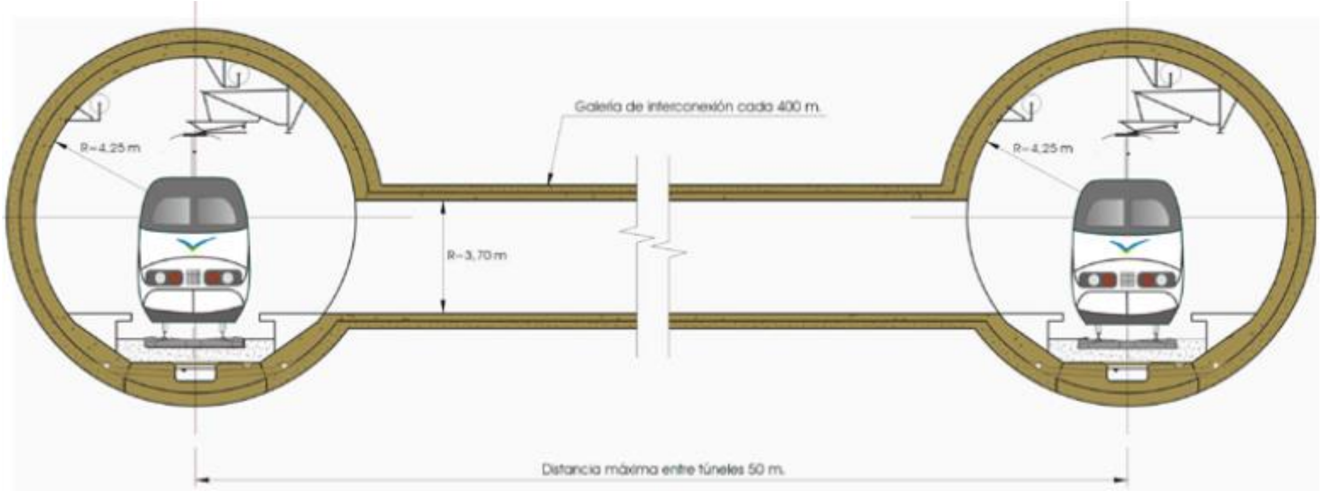
OVERALL CONSTRUCTION STRATEGY

- Construction divided into **four major contracts** (Lots 1 to 4).
- Five TBMs operating simultaneously across multiple access points.
- Combination of TBM excavation and conventional methods.
- Extensive system of underground logistics, access galleries, caverns, and cross-passages.

SCOPE OF WORKS – LOT 1

SCOPE OF WORKS

- **West tunnel: 11.05 km**.
- **East tunnel: 9.87 km**.
- **24 cross passages**: every 400m, length 50m, 14m2 section.
- **Intermediate access via the Folledo Gallery**: 2 km long, 13.5% descending gradient, connecting to the main tunnels through a cavern.



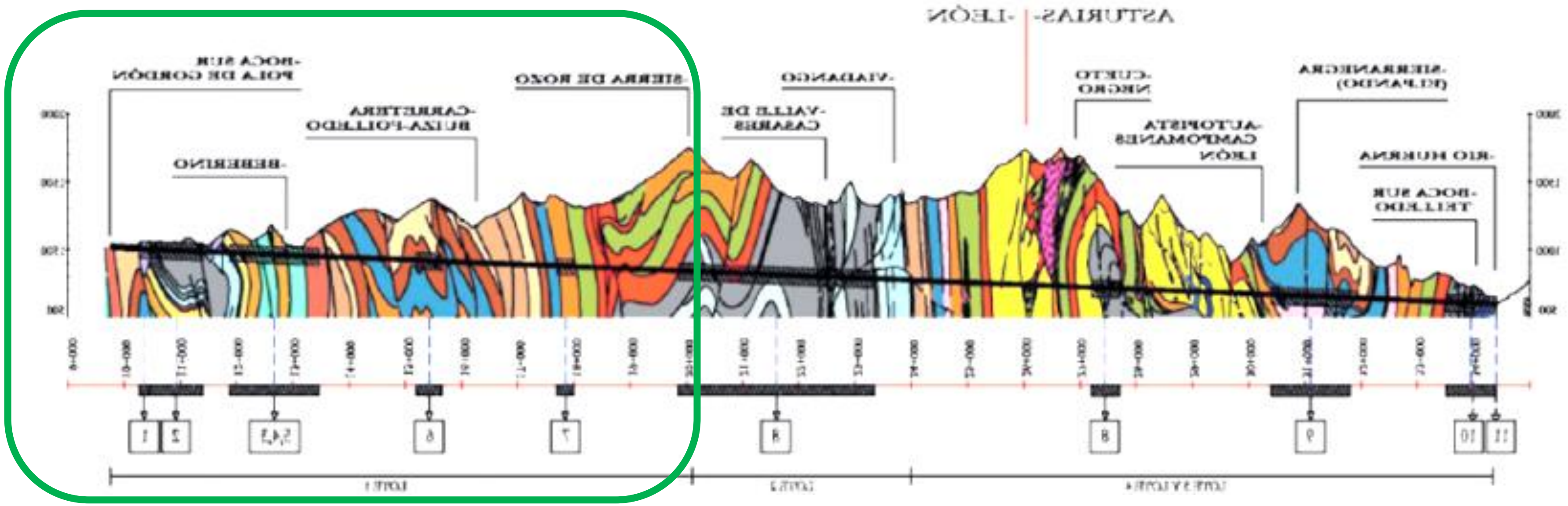
ADDITIONAL FEATURES

- Excavation with **2** hard rock **TBMs**.
- TBM disassembly cavern.
- Segmental lining with **8.5 m internal diameter**.
- Tunnels cross-section of 52 m^2.
- Gradient: constant **16.85‰** descending slope.
- Construction timeframe: **04/2004 to 04/2011**.

CONSTRUCTION CHALLENGES

- Long TMB drives.
- Exceptionally high **overburden** close to **1,000 m**.
- Variable ground conditions.
- **Karst aquifers** with **unpredictable/massive groundwater inflows**.
- Descending tunnel gradient.
- High-strength concrete lining for **high in situ stress conditions**.
- **TBM removal in an underground cavern**.

GEOLOGICAL CONDITIONS



KEY CONSIDERATIONS

- **High-volume water inflows**.
- Variable excavation performance.
- Need for adaptive tunnelling strategies.
- Approximately **35% of the alignment in low-quality shale formations with significant squeezing potential**.
- Potential presence of **methane gas** due to coal-bearing Carboniferous formations.

MAIN GEOTECHNICAL FORMATIONS

- Karstified limestones (Valdeteja, Santa Lucía) which contain underground cavities and channels formed by water dissolution.
- Schists and phyllites (San Emiliano formation).
- Slates alternating wit sandstone layers.
- Quartzites.

GEOTECHNICAL CHALLENGES

- Frequent geological transitions.
- Strong **heterogeneity**.
- **Karst cavities**.
- Highly **variable permeability**.
- Highly **fractured rock masses**.
- **Unpredictable groundwater flows**.

GEOLOGICAL CONDITIONS

OVERBURDEN & GROUND PRESSURE

- **Overburden up to 1,000 m**.
- Lithostatic pressures up to 25 MPa.
- Hydrostatic pressures up to 6 MPa.

IMPLICATIONS

- High in-situ stresses (**high stress on lining segments**).
- Stability challenges.
- Potential deformation zones.
- Strong loads on lining segments.
- **Need for high-performance segments**.

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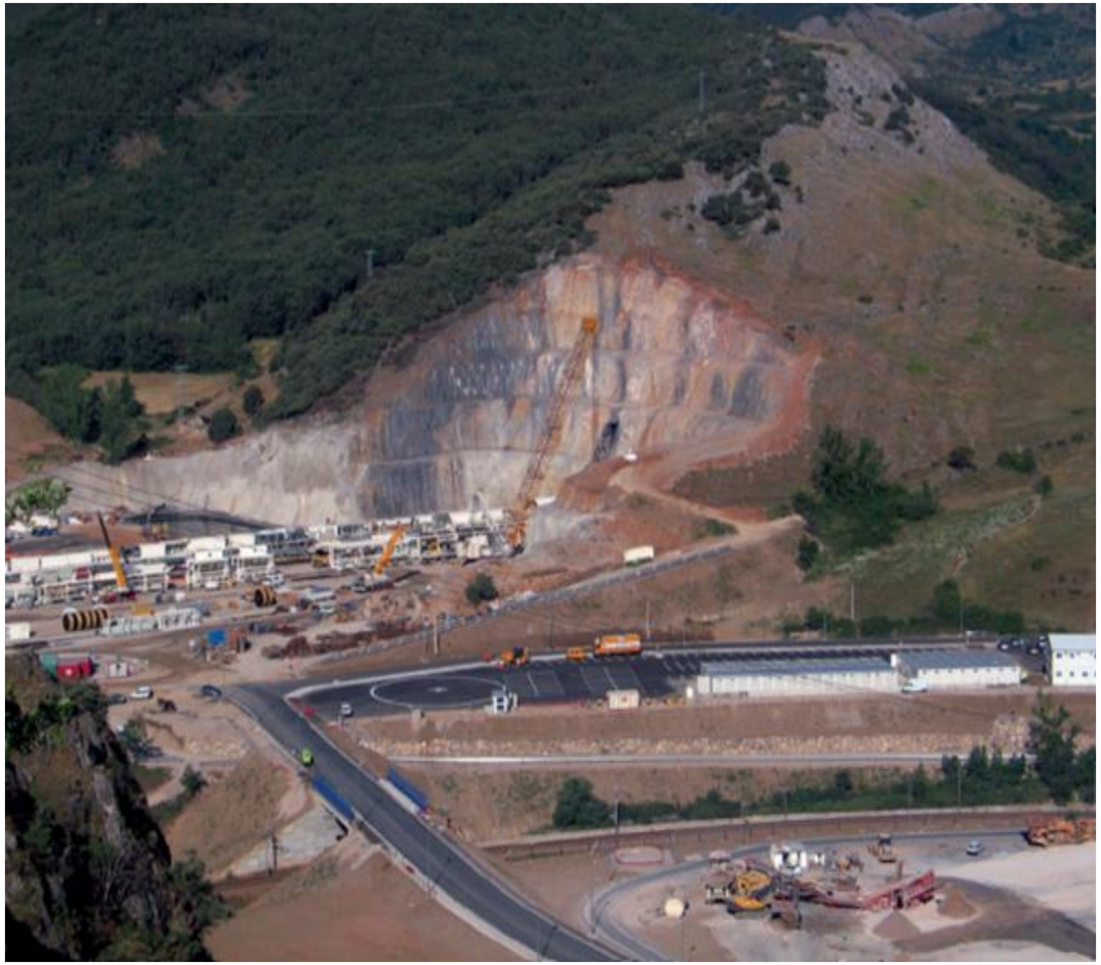


GEOLOGICAL CONDITIONS

STRENGTHENED GROUND INVESTIGATIONS

1. **Comprehensive supplementary geotechnical campaign** during construction:
    - Additional drilling, geological mapping & lab testing.
    - Deep boreholes + structural & hydrogeological analyses.
2. Improved geological understanding through **refinement of the ground model** to anticipate squeezing, water inflows and methane-bearing formations.
3. Enhanced **predictive capability** to more accurately identify high-pressure zones, karstic cavities and deformable Carboniferous shales, informing key design and construction modifications.

REAL-SCALE GROUND VERIFICATION – FOLLEDO ACCESS GALLERY

1. Purpose and strategic function:
    - Obtain the **first real-scale geotechnical insight** into the deep rock mass.
    - **Verification of the structural response predicted in the design**.
    - Ensure a safe **alternative excavation route in case TBM performance becomes uncertain**.
2. Execution approach:
    - Excavated using NATM, enabling continuous geological mapping, adaptive support installation and detailed deformation monitoring.
    - Designed with a **13.5% descending gradient** to minimise length and construction time while providing ventilation, drainage and logistical support for conventional headings.

HYDROGEOLOGICAL CONDITIONS

HYDROGEOLOGICAL CHALLENGES

- **Karst aquifer intersections.**
- **Highly permeable** limestone formations.

IMPLICATIONS

- Flooding risk.
- Drainage of karst aquifers.
- Operational difficulties.

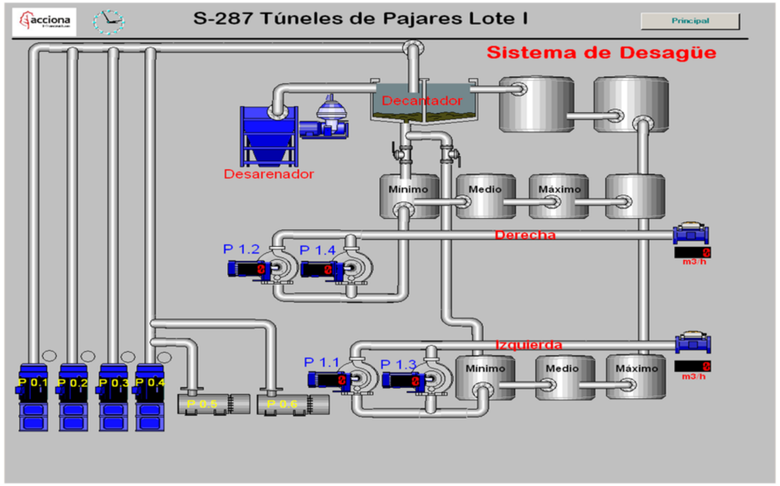
EXTREME GROUNDWATER INFLOWS

- **Average** inflow: **200–300 L/s**
- **Peak** inflows: **>500 L/s**
- Tunnels acting as drainage structures.

EXTREME GROUNDWATER INFLOWS – CHALLENGES & RESPONSE STRATEGY

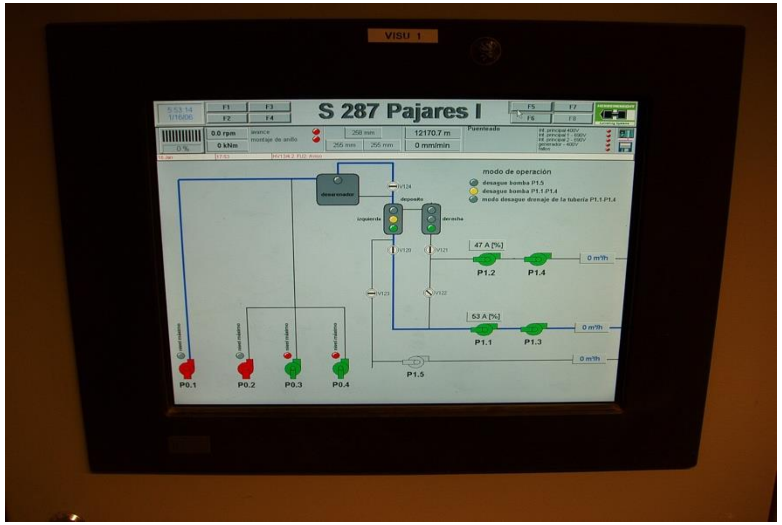
HYDROGEOLOGICAL CHALLENGES

- Extreme groundwater inflows, with **pumping power demand sometimes exceeding TBM power consumption**.
- The 1.68% negative gradient caused all inflows to accumulate at the TBMs, far exceeding onboard pumping capacity.
- Excavation continuity required a distributed **multi-stage pumping system** capable of handling sustained inflows of hundreds of L/s over 15 km.



PREVENTIVE & CONTROL MEASURES

- **Exploratory boreholes** to detect water-bearing fractures and karstic voids.
- **Drainage boreholes** to depressurise the rock mass ahead of excavation.
- **Waterproofing injections** to reduce inflows and stabilise fractured zones.
- Pumped water routed to the surface for treatment prior to discharge.



EARLY DETECTION OF WATER-BEARING GROUND

BEAM system (**Boring Electric Ahead Monitoring**) installed on the lead TBM:

- Low-frequency galvanic currents + three-electrode configuration.
- Detection of fractured or karstified zones up to ~30 m ahead (≈3 TBM diameters).
- Enabled anticipation of potential high-inflow zones.

MULTI-STAGE PUMPING SYSTEM – ARCHITECTURE, CAPACITY & OPERATION

SYSTEM ARCHITECTURE

- Network of **multi-stage pumping stations** (8no.) located in cross passages every ~2 km.
- Intermediate tanks (~290 m^3) at each station for settling and flow regulation.
- Folledo cavern equipped with a larger cascading tank totalling 553 m^3 system for primary decantation and sediment removal.
- Cross passages repurposed as intermediate pumping chambers.

PUMPING EQUIPMENT & PERFORMANCE

- **High-capacity pumps** enabling long-distance water transfer between stations.
- Combined system capable of managing hundreds of litres per second under extreme inflows.
- **Bypass capability** allowing pumping to continue even if one station is offline.

POWER SUPPLY & REDUNDANCY

- **Dedicated 20 kV power** line feeding all pumping stations.
- **Emergency generators** ensuring uninterrupted pumping during power outages.
- Centralised monitoring and automated pump control for reliable operation.

OPERATIONAL OUTCOME

- **Safe and continuous excavation** despite extreme hydrogeological conditions.
- Controlled management of inflows, preventing sudden water eruptions.
- **Environmental compliance** ensured through **surface treatment before discharge**.

TBM DESIGN & GROUND RISKS

TBM TECHNICAL SPECIFICATIONS

Two single-shield hard-rock TBMs:

- West tunnel: Herrenknecht, Ø 9.90 m, 64 cutters + 4 central cutters, 250 m total length.
- East tunnel: NFM Wirth, Ø 9.93 m, 71 cutters + 6 central cutters, 192 m total length.

METHANE & VENTILATION SYSTEMS

Methane risk due to Carboniferous shales.

- Comprehensive **methane detection systems**, with 14 gas detectors strategically placed along each TBM to ensure continuous monitoring.
- **Enhanced ventilation capacity** with dual blowing and suction lines (36–72 m^3/s blowing; 25 m^3/s suction) to manage potential gas pockets.
- **Safety controls** incl. **automatic shutdown of excavation** when gas concentrations exceed predefined thresholds.

HIGH-STRESS / SQUEEZING GROUND

- Carboniferous shale formations with squeezing behaviour.
- Overburden >300 m in critical zones → **entrapment risk**.
- Need for robust face control and stable ring installation.

TBM OPERATION & OPTIMISATION

WHY SINGLE SHIELD TBMs

- **Single-shield TBMs selected over the initially recommended open machines** to improve control and minimise entrapment risk in deep, high-pressure ground.
- **Short shields** adopted to reduce entrapment risk under >300 m overburden in shale formations.

THRUST, BACKFILLING & STABILITY MEASURES

- **Maximum thrust** increased to **180,000 kN** to overcome squeezing ground and to reduce the risk of shield entrapment.
- Mortar backfilling adopted for reliable annulus filling under high water inflows, replacing the initially proposed gravel + grout, which acted as a drain and increased washout risk.

CUTTER WEAR MANAGEMENT

High rock abrasivity and strength, combined with the need to sustain high excavation rates, led to the installation of an **on-site cutter repair and refurbishment workshop** for both TBMs.

TBM PERFORMANCE OVERVIEW

Average TBM advance rates were not exceptional, but **achieving the planned schedule in such complex geology is a remarkable success**.

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ULTRA-HIGH-STRENTH SEGMENT LINGING

KEY DRIVERS

- **Overburden up to 1,000 m** → very high in-situ stresses.
- Deformable shale formations → **squeezing behaviour**.
- Karstified limestones → **unpredictable / high groundwater inflows**.
- **High hydrostatic pressure** acting on the lining.
- Need for **durable, low-permeability lining** under aggressive hydrogeological conditions.

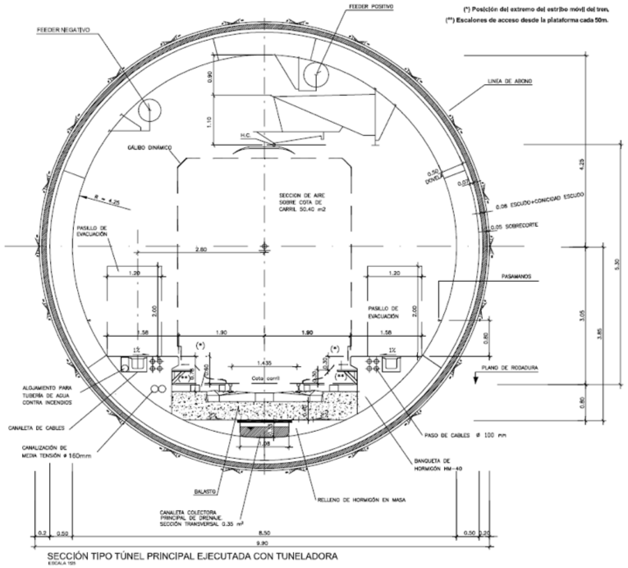
DESGIN RATIONALE & BENEFITS

Decision to **increase concrete strength while keeping the standard 0.50 m segment thickness**:

- Avoided the need for a larger excavation diameter.
- Eliminated the need for a different TBM configuration.
- Reduced overall construction costs compared to increasing segment thickness.

ENGINEERING SOLUTION

- **Ultra-high-strength concrete**, with **characteristic strengths up to 105 MPa and measured values exceeding 115 MPa**.
- Very low permeability, with **water penetration < 0.5 mm**, improving durability and resistance to aggressive groundwater conditions.
- Standard segment thickness maintained at 0.50 m.
- Enhanced long-term durability and structural performance.



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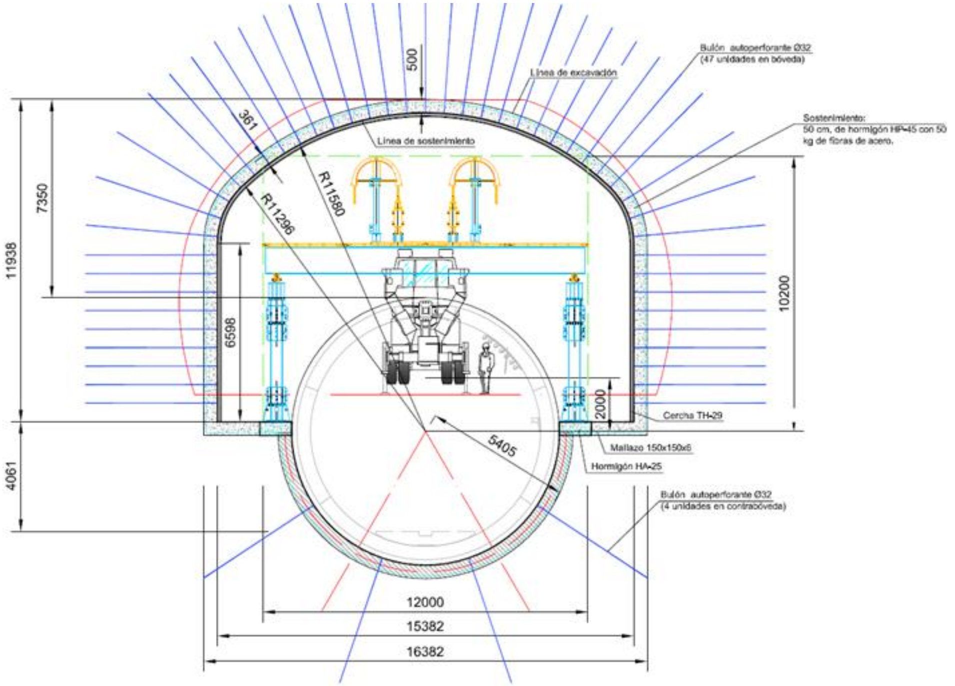
TBM DISASSEMBLY CAVERN

CONSTRUCTION SEQUENCE

- <u>Phase 1</u> – **TBM excavation – 80.12 m^2**:
  - Final 36 m excavated without installing the full segmental lining.
  - Temporary support installed directly from the TBM using sprayed concrete and bolts.
  - Excavation advanced in 1.5 m strokes, with support placed immediately after the shield passed.
- <u>Phase 2</u> – **extension of the tunnel section – 217 m^2**:
  - TBM backup removed after completing Phase 1.
  - Tunnel section enlarged using conventional excavation with explosives.
  - Temporary support installed with sprayed concrete and bolts (no steel ribs required).
  - Gantry crane installed inside the cavern to dismantle the TBM.
  - Cavern later adapted as an underground passenger rescue area.



EXCAVATION BY CONVENTIONAL D&B METHODS

- Length: **30 m**
- Width: **17 m**
- Height: **19 m**
- Excavated section: **287 m^2**

KEY CONSTRUCTION MODIFICATIONS IMPLEMENTED BY LOT 1 CONTRACTOR

1. **SHIFT IN EXCAVATION STRATEGY**
   - Replacement of the initially recommended open TBMs with **single-shield hard-rock TBMs**.
   - **Extension of TBM excavation to the entire 10.5 km**, eliminating the 2.6–2.7 km NATM section originally planned.
2. **TBM REDESIGN FOR EXTREME GROUND CONDITIONS**
   - **Short-length shield design** to reduce entrapment risk in highly deformable shales.
   - **Maximum thrust increased to 180,000 kN** to overcome severe squeezing and high-pressure zones.
   - **Reinforced pumping capacity** (**500 L/s**) and high-capacity ventilation (**60 m^3/s**) to manage major inflows and methane pockets.
3. **STRUCTURAL AND MATERIAL ENHANCEMENTS**
   - Adoption of 50 cm precast segmental lining throughout the entire lot.
   - Introduction of **high-strength concrete** (**70–105 MPa**) to withstand lithostatic pressures up to 25 Mpa.
4. **GEOTECHNICAL REASSESSMENT AND ACCESS STRATEGY**
   - **Additional 7,000 m of core drilling** and **reinterpretation of the geological model**.
   - Strategic use of the Folledo access gallery for drainage, geological verification, and TBM logistics.
5. **PROCESS AND SCHEDULE OPTIMIZATION**
   - **~20% reduction of excavation volume** achieved by replacing the NATM section with full-section TBM excavation, eliminating excess excavation.
   - **>50% reduction in concrete consumption** enabled by using a single 50-cm precast segment ring instead of NATM's double lining of shotcrete plus cast-in-place concrete.
   - **555-day schedule acceleration** made possible by continuous TBM excavation with immediate segment installation, avoiding the slow sequential cycles of NATM.

STRATEGIC INSIGHTS

- Hydrogeology is critical in long tunnels and must be central in tunnel design.
- **Construction strategies** must remain **adaptable**.
- Importance of **adaptive design.**
- Early **geotechnical investigation.**
- Robust **water management systems.**
- **Continuous monitoring** is essential.
- **Innovative materials**, such as very high-strength concrete, can significantly improve structural performance and durability.
- High-performance materials and TBM technology significantly improve safety and efficiency.
- Extreme geological conditions can be overcome through **innovation.**
- Importance of **hydrogeological investigation**.
- Need for flexible construction strategies to **adapt to geological reality.**

CONCLUSION

- Large underground infrastructure projects like the Pajares tunnels remind us that **true engineering lies in continuously adapting to the behaviour of the ground and water**.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