CERN (HL-LHC): challenges and tunneling experience for the design of new underground structures at Point 5

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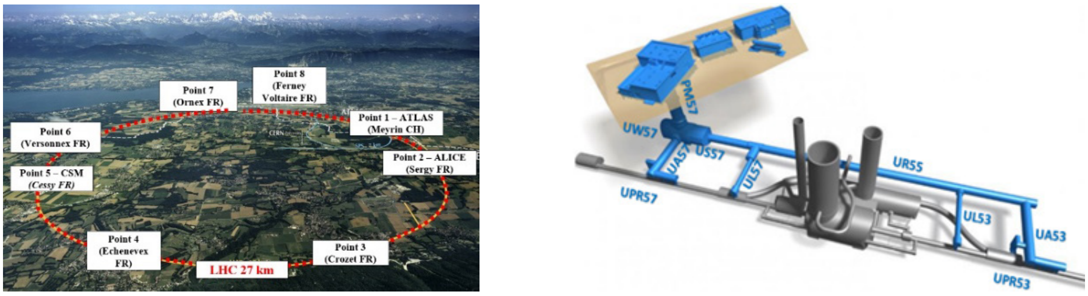
ABSTRACT: This paper deals with the main challenges and design issues raised for the construction of new underground structures at Point 5 close to the largest underground particle accelerator in the world (Large Hadron Collider). The High-Luminosity LHC is a new project aimed to upgrade the accelerator at Point 1 (ATLAS, Switzerland) and Point 5 (CMS, France), by increasing the number of atomic collisions. The new project requires an additional shaft, a cavern, galleries, vertical linkage cores and technical buildings at the surface. To predict the complex response of the heterogeneous rock mass and evaluate the impact of the excavation phases on the nearby existing structures, 2D and 3D finite element and finite difference models were realized, allowing to design both the rock-supports and the concrete inner lining for all the structures. The observational method was applied during the construction phase to verify the hypothesis used in the numerical calculations.

Keywords: Numerical analysis, Rocks mechanics, Underground works, Observational method.

1 INTRODUCTION

CERN, the European Organization for Nuclear Research, is a 23 members organization based in Geneva that enables international collaboration and research in the field of high-energy particle physics (Mattelaer and Lopez-Hernandez 2022). The Large Hadron Collider (LHC) is the world's largest underground particle accelerator placed on both sides of the Swiss-French border. The High-Luminosity LHC is the new project aimed at enhancing the LHC experiments, in order to produce more data by increasing the number of particle collisions. This project will be operational in 2026 and requires new technical infrastructure for the two main detectors, at Point 1 for the ATLAS experiment and Point 5 for CMS experiment respectively, as shown in Figure 1. At Point 5, the new HL-LHC underground structures are placed on the inner side of the existing LHC ring at an average distance of approximately 50 m from the LHC axis and located 7 m above the existing LHC tunnel crown. This paper describes the design challenges and construction issues developed at Point 5 where the new underground structures mainly consist of: i) a new shaft PM57 (ϕ=12m, deep=60m) with at the base a service cavern US57/UW57 (A_{exc}=270m^2), ii) a power converter gallery UR55 (A_{exc}=60m^2), iii) two pairs of service galleries UA57/UA53 and UL57/UL53 (A_{exc}=45m^2 and 20m^2 respectively), iv) 16 vertical linkage cores to the existing LHC (ϕ=1.7m, deep=5m), v) two personnel escape galleries UPR53/UPR57 (A_{exc}=25m^2). All the new underground structures are designed with a double lining system. The design work life is 10 years for the temporary support, 100 years for the final lining and 50 years for the drainage system internal structures. The main challenges are: i) differential settlement arising from the connection between the existing and new structures; ii) the rock mass with potential swelling behaviour and the presence of hydrocarbons; iii) the limitation of the vibrations induced from the excavation.

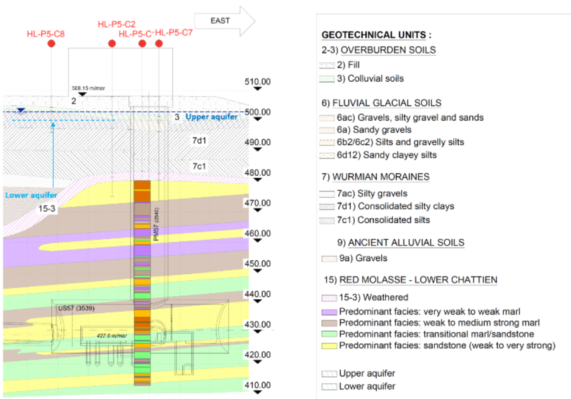


a) b)

Figure 1. a) Overview of the CERN site; b) Underground structures at Point 5.

2 GEOLOGY AND GEOTECHNICAL CHARACTERIZATION

The new underground structures have an overburden of approximatively 60 m. They were excavated through the Molasse unit, except the upper part of the PM57 shaft which extended to a depth of approximately 22 meters which was within the Wurmian Moraines. The Molasse comprised of alternating beds of approximately 50% sandstone, 25% of platy marls and “Grumeleuse” marls, and 25% sandy marls. Layers were typically 0.5 to 5 m thick, and their stiffness varied between the layers. The in-situ geology was consistent with published data confirming that the Molasse was a highly heterogeneous rock mass (Kurzweil, 2004; Canzoneri et al., 2019). The sandstone beds were considered isotropic. The marls were lithologically heterogeneous described as a succession of weak ductile marls, sandy marls and strong marls which were thinly laminated with weak lamination planes with horizontal and inclined joints surfaces. The upper part (typically 1 to 5 m thick) of the Molasse is usually weathered and displays soft soil-like properties. In the Geneva basin, molasse is known to locally retain hydrocarbon fluid and gas. In terms of hydrogeology, 2 aquifers were identified: i) upper aquifer, phreatic, located within the fluvio-glacial soils; ii) lower aquifer, within the underlying moraine. As the permeability of the Molasse obtained from in situ tests was very low ($k < 10^{-7}$ m/s), the rock mass was considered to be impermeable. The K_0 values varied between 1.25 - 2 (rock mass) and 0.7 (soils).



	Weak marls	Weak/ strong marls	Marl/ sandstone	Sand- stone
γ [kN/m^3]	24.0	24.5	25.0	23.0
ψ [°]	0.0	10	18	21
ϕ [°]	18.5	30.0	38	41
ϕ_{res} [°]	17	30	34	34
c [MPa]	1.2	2.6	4.8	2.1
c_{res} [MPa]	0.5	1.3	1.6	1.0
σ_c [MPa]	3.2	9.4	20	9.1
E_{mc} [MPa]	500	1260	3000	1500

Figure 2. Geological profile at Point 5 and rock mass parameters.

3 NUMERICAL ANALYSIS DURING THE DESIGN PHASE

3.1 *Vibration issue: Finite Difference analysis*

The minimization of the vibrations induced by the excavation of the PM57 shaft to the nearby LHC tunnel while experiments were in progress represented one of the main issues of the HL-LHC project. Different excavation techniques were considered (Table 2) and 3D Finite Difference (FD) analysis allowed to estimate the induced vibrations. Two inputs were considered in the numerical models performed by FLAC 7.0 software (Itasca): simple sine wave up to a frequency of 10 Hz in the soil and 35Hz in the rock, and signals matching the spectra of the considered excavation methods. In order to determine the amplification of the input vibrations, several horizontal or vertical input signals are implemented at the excavation face for several shaft excavation steps. The response of the model in terms of displacements is then recorded at locations of interest. A total of 328 numerical simulations have been carried out. The vibration threshold values were set according to the results of the FD sensitivity analysis of the existing structures, as specified in the Client contractual documentation, while the contract permitted the Owner to stop the excavation works at any time and impose a change of excavation method if the threshold criteria were exceeded.

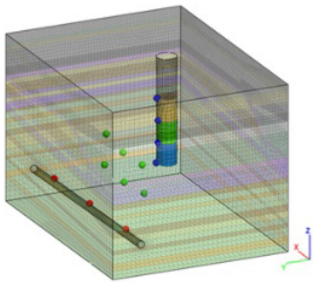


Figure 3. FD model.

Table 1. Excavation methods.

Excavation technique	Description
A	mechanically assisted tunneling in rock with electrical Road Header
B	mechanically assisted tunneling in rock with Rock Breaker
C	excavation with Hydraulic rock splitter inside previously drilled holes
D	bucket excavator

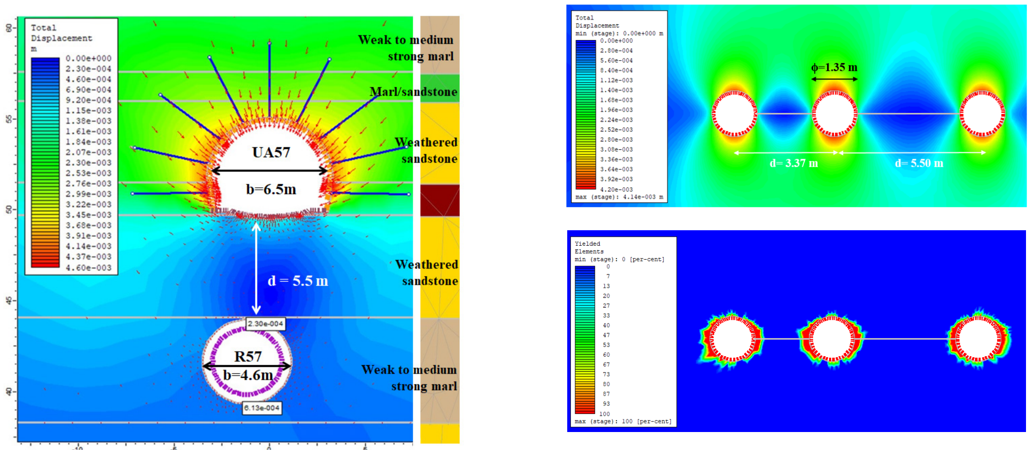
3.2 *Rock supports design and mutual interactions: Finite Element analysis*

The heterogeneity of the rock mass was investigated by performing FE 2D analysis, under plane strain conditions using RS2 9.0 (RocScience). The results assessed the potential impact on the existing underground structures, provided the design of the rock- supports, and provided the design of the final concrete inner lining. Numerical models were created to represent various standard cross-sections and rock support classes were modeled according to the critical narrow tunnel geometric configurations for different geotechnical scenarios in terms of thickness and location of the molasse layers. An elasto-perfectly plastic Mohr-Coulomb criterion was adopted.

The FE model used to model the excavation of the new UA57 tunnel, which is located at a minimum distance of approximately 5.5 m above CERN's main ring (R57), is shown Figure 4a. For the existing R57 ring, the lining was modelled as a standard beam of unreinforced concrete C25/30 22cm thickness. For the UA57, the rock support class 2 was modelled as follow: shotcrete C20/25 25cm thickness, lattice girders 3G 70/20/26 (spacing of 1.2 m) and radial fully grouted bolts L = 4.00m, $F_{tk} \geq 250$ kN (spacing in plane of 1.50m and out of plane of 1.20m). This FE model also confirmed a predominantly elastic rock mass behaviour with narrowed plastic zones that were not in contact with the nearby tunnels. The increase in displacements in the existing R57 tunnel was estimated to be a maximum of 1 mm, so that it was concluded that no additional supports were necessary for the existing LHC.

The excavation of the vertical cores close to their connection with R57 ring is given Figure 4b (plane section) under the assumption of K_0=2.0 (σ_1) and K_0=1.25 (σ_3). The structure of the vertical cores (excavation diameter=1.35m, spacing 3.37m/5.50m) mainly consists of steel cylinder S235, 15mm thickness, backfilled with free-flowing concrete. This FE model also confirmed a predominantly elastic rock mass behaviour with narrowed plastic zones that were not in contact with the nearby cores. The displacements were estimated to be a maximum of 2-3mm, while stresses are compatible with the steel cylinder strength.

Same conservative geotechnical parameters were adopted as those used in the models analyzed using RS2 2D software to evaluate the sections near the several crossing zones where 3D effects are critical, and the inner lining was reinforced only in the crossing zones as resulted from the outcomes of the 2D numerical models. Finally, stresses acting on the final supports were also successfully compared with those obtained from simplified beam-spring 2D models that allowed to take into account the loads induced by temperature, swelling and creep effects according to the load combinations stated in Eurocode.



a) b)

Figure 4. FE model results: a) evaluation of total displacements induced by the excavation of UA57 tunnel on the existing LHC ring (Merlini et al., 2022; b) evaluation of the total displacements (top) and yielded zone (bottom) due to the excavation of the vertical cores connecting UA57 tunnel with R57 ring.

4 THE CONSTRUCTION EXPERIENCE AND THE ROLE OF NUMERICAL ANALYSIS DURING THE CONSTRUCTION PHASE

A comprehensive monitoring system was installed to check the response of the variable soil units and heterogeneous rock mass. The displacement on new and existing structures during the excavation works were measured by means of high-precision instrumentation: i) optical displacement points, ii) multiple point extensometers and iii) sliding micrometer (Figure 5). The underground works where CERN instrumentations for the ongoing tests are placed, had to remain below the threshold of 1mm and generally this very restrictive threshold was not exceeded. Moreover, the outcomes of a monitoring system were compared to the 2D FE results, thus confirming the importance of the observational method to verify the hypothesis assumed in the numerical modelling during the design phase. The monitored convergence for the new underground structures were a maximum 1cm. The evaluation of actual ground conditions encountered during the excavation stage, also allowed some optimizations of the rock supports. Figure 6a shows the back-analysis model for the UR55 tunnel to assess the lower rock bolts' removal, thus allowing an increase in excavation rate and a reduction in project costs. The models' results showed that the structural safety was still within threshold values and that the effects on the nearby structures were similar to those in the original design solution.

Based on the encountered ground conditions, an axial-symmetric FEM model was created to re-evaluate the rock load acting on the final lining of the shaft PM57. Based on the re-evaluated rock load (from 520 kPa to 400 kPa), the internal stresses acting on the final lining of the shaft were estimated by means of beam-spring 2D models. The model was created by using Statik 9.0 code (Cubus), also allowing to consider the loads induced by temperature, swelling and creep effects according to the load combinations stated in Eurocode (Figure 6b). The final lining has been modelled as concrete beams 0.60m thickness, 1.0 m width, concrete C35/45, Young's modulus E = 35 GPa, Poisson ratio v = 0.17. Rock-structure interaction was modeled with non-linear "compression-only" springs whose normal compressive stiffness has been evaluated by means of the Galerkin formula by considering a reduced elastic modulus of the rock-mass (creep effects). Tangential stiffness of the radial springs has been assumed equal to zero due to the installation of waterproofing layer between primary and final lining. In order emphasize the anisotropy of the soil and to maximize the bending moment on the final lining, an axial-symmetric distribution of the load is adopted. ULS and SLS checks were performed: the horizontal and vertical steel reinforcement consists in Ø14 spacing 15cm on both sides and concrete cover equal to 50mm, while no shear reinforcement was need. This optimization allowed to save about 40% of the overall steel reinforcement.

Triaxial orthogonal seismometer, force balance accelerometer and 2 accelerometers were adopted to monitor the vibrations during the excavation of the shaft and their positions were changed according to the progress of the excavation. The effective sequence of excavation for the shaft was as follows: the first 20 m of the shaft was excavated with a bucket, which was replaced by the Road Header in the rock until 56 m depth and completed using the Rock Breaker. The excavation of the galleries and cavern mainly adopted the Method B. The measured vibrations were always far from the attention value.

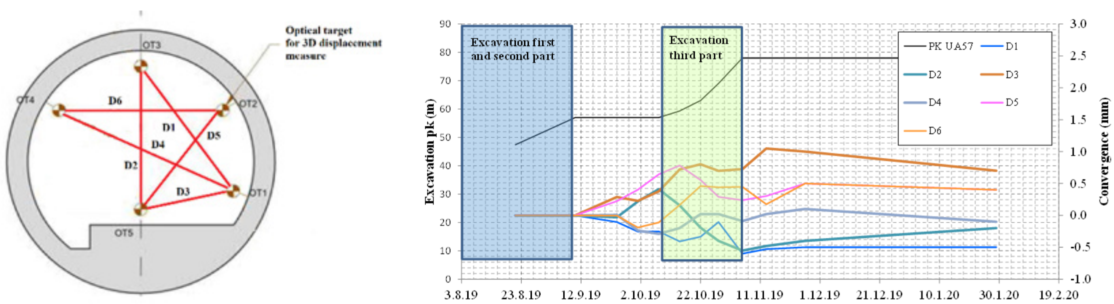


Figure 5. Example of monitoring section for the main existing ring with trend of displacements and indication of 1st and 2nd part of excavation (min. distance between existing and new underground works equal to approx. 20 m) and 3rd part (min. distance between existing and new underground works equal to 5.5 m).

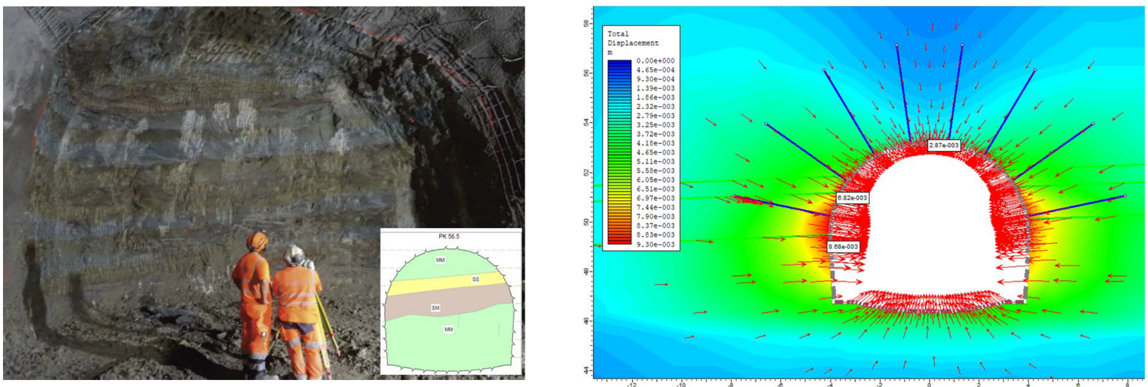


Figure 6. Back-analysis for the optimization of rock supports at UR55 tunnel.

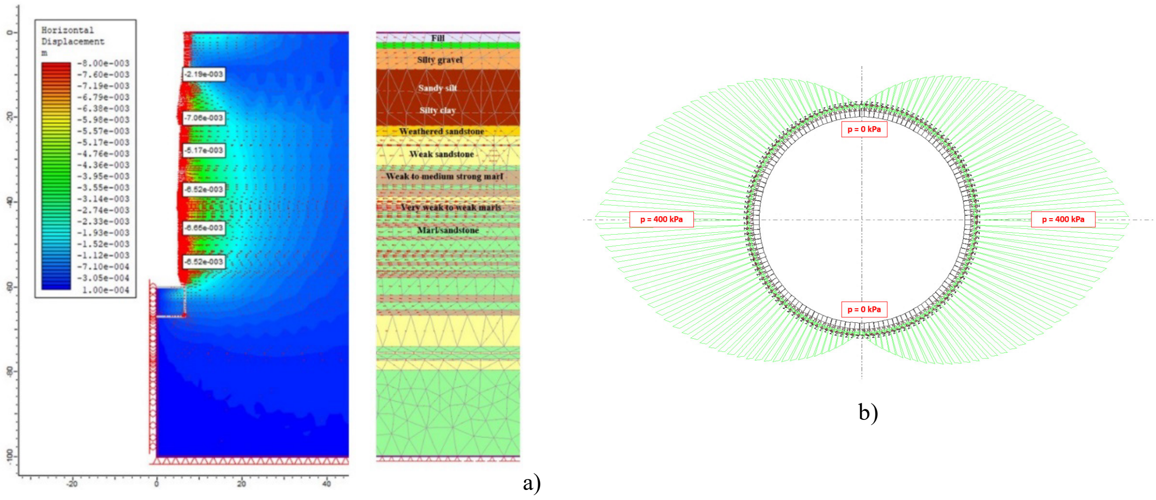


Figure 7. Back-analysis of Shaft PM57: a) axial-symmetric FE model showing horizontal displacement calculated from the cross-check geology; b) Beam-spring model of the PM57 shaft: geometry and load distribution.

5 CONCLUSIONS

The main challenges and the tunneling experience gained during the underground works at Point 5 HL-LHC Project at CERN are presented in this paper. The benefits of performing reliable FDM and FEM analysis both in the design and the construction phases are also presented for some relevant underground structures. Numerical modelling was a key tool to simulate many excavation phases in heterogeneous rock-masses allowing the evaluation of the potential impact of the excavation works on nearby structures. A comprehensive monitoring system allowed to confirm the assumption made during the design phase and permitted optimizations of the design of the supports, allowing a reduction in project costs. Total construction cost for civil works at Point 5 was 58 Mio €, among them 25 Mio € for the underground structures. The excavation of the underground works started in April 2018 and, despite the proximity to the nearby existing underground structures, all the underground structures have been completed in December 2022 without any critical impact.

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