Tunnelling Studies for CERN's Future Circular Collider

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ABSTRACT

CERN, the European Organisation for Nuclear Research, has started planning for a future upgrade of their particle accelerator complex located in the Geneva basin, straddling the France/Swiss border.

Studies are currently under way for the planning and construction of the Future Circular Collider (FCC) project which will allow the scientific community to expand their knowledge on particle collisions at high energies. In order to achieve this goal, the FCC will require extensive civil underground infrastructure including a 100km long 6m diameter circular tunnel, 20 large shafts, several caverns with spans of up to 30m and multiple connecting tunnels and galleries. These structures will be built in a variety of ground conditions from hard limestone and molasses to water bearing glacial deposits. This paper discusses the project layout and planning challenges.

1. INTRODUCTION

The FCC study is developing options for high energy colliders at CERN for the post-Large Hadron Collider (LHC) era. The study was formally launched in response to the recommendation made in the 2013 update of the European Strategy for Particle Physics that “Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines.” (CERN 2014).

From a Civil Engineering perspective, the study has been focussed on verifying the feasibility of the project, finding a suitable location and defining the structures necessary to house the FCC.

2. HISTORY OF TUNNELLING AT CERN

CERN has been building underground structures on the French-Swiss border since the 1950s. The first major underground project on the Meyrin site was the Super Proton Synchrotron (SPS), which is a circular collider with a 7 km circumference; it was constructed using a TBM with an average depth of 40 m below the ground surface. This was followed by the infrastructure for the Large Electron Positron (LEP), which was constructed between 1983 and 1989. The LEP accelerator required a 27 km ring tunnel, which was later adapted to accommodate the LHC from 1998 to 2005. This tunnel, which sits at on average 100 m below the surface, was excavated using 3 TBMs and one sector of drill&blast. The majority of the tunnel was excavated in the variable sandstone layer known locally as molasse and a short sector was excavated in limestone using drill&blast. The tunnelling through the molasse layer was executed without any major problems and a maximum rate of 58.7 m per day was reached. However, approximately 3 km of tunnelling was required through the limestone at the foot of the Jura mountain range, which proved more challenging. Even though continuous pilot borings were made ahead of the blast face, there was still a major geological incident where a water ingress with a rate of 100 l/s at a pressure of 8.5 bar occurred. In order to overcome the water flow, resin injections and drainage of the tunnel were required, resulting in an 8 month delay. The final breakthrough in the tunnel was achieved in February 1988 (Schopper 2009).

For the upgrade of the underground assets for the LHC, additional shafts and large span caverns were required to house new detectors and equipment. The caverns, with a maximum span of 35 m, were some of the largest span caverns constructed in the world in this type of geology. However, the most challenging aspect of the works proved to be the excavation of the large shafts through the top layer of water-bearing glacial deposits, of up to 50 m in depth. High groundwater flow rates led to the need for ground freezing to be adopted.

The underground infrastructure required for accelerators at CERN represents a substantial proportion of the risk and approximately one third of the total consolidated cost of the projects (C. Cook 2015), and hence considerable importance is placed on the civil engineering design at the feasibility point of studies.

3. PROJECT LAYOUT

It is envisaged that the FCC infrastructure will host the world's largest particle accelerator. The layout for the tunnelling works, which has been developed by CERN and proofed by ILF, is currently at a conceptual stage. The project alignments and structural shapes might undergo significant changes in the coming years as the operation requirements and civil works designs are further developed.

The FCC underground civil works include the construction of an almost circular 97.75 km tunnel ring. The ring will have some major additional underground structures that will be connected to the surface sites at 12 points along the circumference (A to L). Figure 3.1 shows a schematic 3D view of the civil works described below:

- A 97.75 km 6 m diameter tunnel located at depths varying approximately between 50 m and 650 m (hereafter called Machine Tunnels);

- Two 6 m diameter tunnels of 4.7 km and 7.1 km respectively, connecting the Machine Tunnels to the LHC (hereafter called Beam Transfer Tunnels);

- Two 2 km long, 6 m diameter tunnels at point D (hereafter called Beam Dump Tunnels);

- Two 10 m high, 20 m wide, 50 m long caverns at the interface between the Machine Tunnels and the Beam Transfer Tunnels (hereafter called Injection Caverns);

- Two 10 m high, 10 m wide, 50 m long caverns at the interface between the Beam Dump Tunnels and the Machine Tunnels (hereafter called the Beam Dump Caverns);

- Several 6 m diameter tunnels with a total length of 15.2 km connecting underground service facilities and the Machine Tunnels (hereafter called Bypass Tunnels);

- Eight 12 m diameter and four 18 m diameter shafts with depths varying between 50 m and 560 m connecting underground service facilities to the ground surface (hereafter called Service Shafts);

- Twelve 15 m high, 25 m wide caverns with lengths varying between 100 m and 150 m and located at the bottom of the Service Shafts (hereafter called Service Caverns);

- Thirty 10 m, 20 m wide caverns with lengths varying between 30 m and 100 m and at the interfaces between the Machine Tunnels and the Bypass Tunnels (hereafter called Junction Caverns);

- Sixty-Six 6 m diameter, 25 m long underground rooms connected to the Machine Tunnels at roughly 1.5 km spacing (hereafter called Electrical Alcoves);

- Eight 10 m and 15 m diameter shafts connecting underground experiment facilities to the ground surface with depths varying between 120 m and 260 m (hereafter called Experiment Shafts);

- Four 35 m high 30 m wide 66 m long caverns at the bottom of the Experiment Shafts (hereafter called Experiment Caverns);

- Forty-eight passage tunnels with 3 m spans and a combined length of 1.3 km connecting the Machine tunnels to the Bypass Tunnels (hereafter called Connection Tunnels);

- Twelve 2 m diameter shafts connecting the Machine Tunnels with the ground surface (hereafter called Survey Shafts);

- Eight 3 m diameter tunnels connecting the Experiment Caverns to the Machine Tunnels (hereafter called Survey Galleries).

The structures listed above form the ‘Baseline Design’, which is the infrastructure required for a hadron or ‘hh’ accelerator. In addition, there are two layout variations that are also under consideration. These variations include the infrastructure required to accommodate a lepton collider ‘ee’ and a hadron electron collider ‘eh’. If adopted, the lepton collider would be run within the 97.75 km tunnel prior to the installation of the hadron machine; the lepton machine requires enlargement of the Machine Tunnels to spans of up to 20 m at points A and G with a combined length of 3.6 km. The ‘eh’ machine would run at the same time as the hadron collider housed in a separate tunnel, which is shown in red on figure 3.1.

The eh machine requires:

- An additional length of 9.1 km of Machine Tunnels;
- Two 175 m deep Service Shafts;
- Two 20 m span 30 m long Service Caverns;
- A 30 m span 30 m long Injection Cavern;
- Two 12 m span 20 m long Dump Caverns;
- 180 m of 5 m diameter Dump Tunnels;
- Bypass tunnels with a combined length of 2.1 km;
- Two 12 m and 20 m span 55 m long Junction Caverns;
- Fifty 1 m diameter Waveguide Passages with a combined length of 0.5 km.

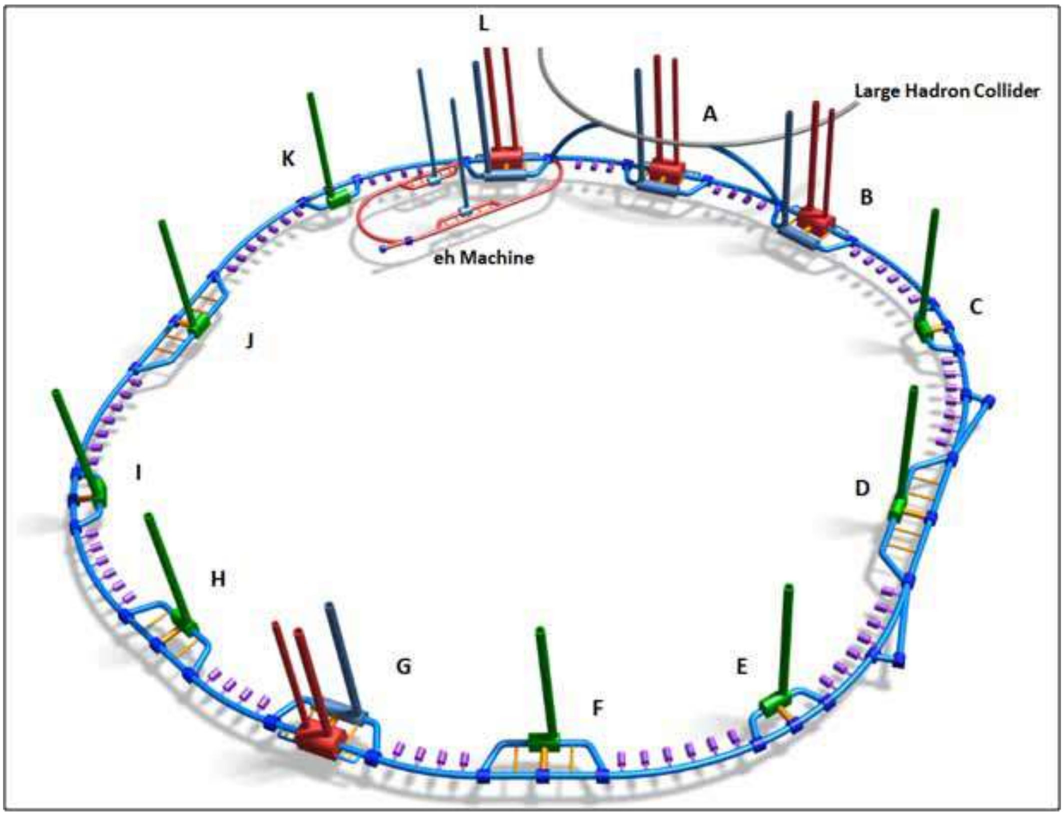

Figure 3.1: FCC 3D Schematic

The twelve underground sites (A to L) require large surface works that will accommodate other necessary infrastructure such as transformers, helium tanks and cryogenic plants, as well as offices for operations and management.

- All experimental sites (A, B, G and L) will have each approximately the same infrastructure: Eight steel frame buildings, seven concrete buildings, transformer foundations, access roads, construction roads and car parking.

- All service sites (C, D, E, F, H, I, J and K) will have each approximately the same infrastructure: Seven steel frame buildings, five concrete buildings, transformer foundations, access roads, construction roads and car parking.

4. GEOLOGICAL SETTING

The project is located in the Geneva Basin, which contains molasse deposits from the Oligocene and Miocene ages. The molasse is overlaid by glacial moraines from the Quaternary and intruded by limestones. A brief description of these deposits is given below.

4.1. Soft Ground Deposits

Soft ground deposits comprise moraines, which are fluvio-glacial deposits and fluvio outwash deposits. Although this material has been characterised extensively for previous projects, it shows marked heterogeneity that cannot be fully captured through boreholes. Moraine deposits typically include sands, gravels, clays and silts with variable permeability, compaction and stiffness. It is entirely possible for moraines to contain large boulders which are undetected by site investigations. Previous projects at CERN have found high geotechnical variability in terms of cohesion, internal angle of shear resistance and stiffness with values for the latter varying between 8MPa and 200MPa.

Some layers are water bearing and, when separated by more impermeable layers, might form various groundwater levels. As noted from previous CERN projects, large water inflows may be expected in excavations. Adequate water control would require the use of ground freezing, grouting or/and pressure balanced excavations. An approximate geological profile (see Figure 4.1.) shows that moraine (dark grey) will be encountered when excavating most of the shafts and the Machine Tunnels under Lake Geneva between points B and C.

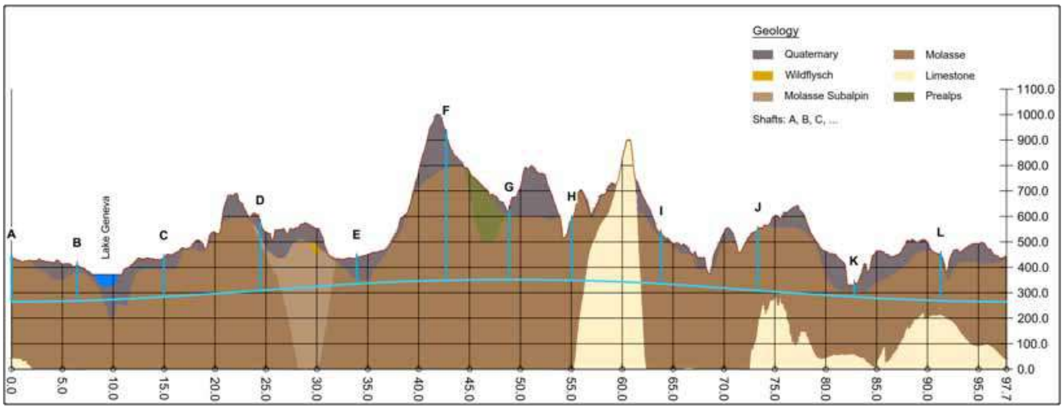

Figure 4.1: Geological Profile

4.2. Rock Deposits

Rock deposits comprise limestones (light cream colour in Figure 4.1) and molasse (See deposits in brown and light brown in Figure 4.1), which are alternating marls and sandstones. Individual layers vary in thickness between 0.1 m and 3 m.

In general, limestones are nodular with marl matrix of high strength. For the FCC project, it is likely to encounter highly dissolved rock masses leaving cavities prone to large water permeability (karst). Although previous projects have found rock UCS strengths between 20MPa and 145MPa, it is reasonable to expect weaker materials.

From the currently available geological information obtained from existing geological reports and drilling records, it is expected that marls and sandstones belonging to the molasse would have UCS strengths varying between 5MPa and 40MPa. It is also possible that these materials will have tight joints and low rock mass permeability, which would result in relatively dry excavation conditions. In contrast, limestone excavations might have large water inflows that require groundwater control measures.

Hydrocarbon contaminated ground might be found at depth. It is possible that concentrations are sufficiently low as to not require special measures during construction; however, it is also entirely possible that excavation works will need to be planned from the point of view of the obvious H&S risk. In addition to this, the durability of the waterproofing systems (i.e. gaskets and membranes) could be compromised by hydrocarbons.

4.3. Structural Geology

There are several known faults in the area including the Allondon and Mandallaz Faults. The tunnel that hosts the LHC and other tunnels in Geneva have encountered these faults in the molasse with no significant excavation difficulties. In general, the risk of water ingress through karstic zones in limestones is higher than the one posed by faults.

5. HORIZONTAL ALIGNMENT

Since the study was launched in 2012 various shapes and sizes for the machine ring have been considered, these have ranged from 47 km to 100 km circumference rings in addition to less conventional “racetrack” shapes. The smallest options were ruled out early-on, even though they carried the lowest risk for civil engineering, as the accelerator would not be able to reach adequate energies. By 2016, an approximately 100 km diameter ring had been adopted by the project team. This ring was initially considered in two distinct positions, one under the Jura, and the other in the molasse basin passing below Lake Geneva. The Jura option was excluded due to the high risk of tunnelling though the karstic limestone with very high overburden.

From 2016 onwards small variations on the chosen position have been evaluated. In the region of the Geneva basin there is limited scope to place a 30 km diameter ring without incurring inadequate connections to the existing particle accelerator, which will be used as an injector complex, or undesirable ground conditions. The strategy for placement has been to avoid the limestone of the Jura and Pre-Alps, whilst also aiming to minimise tunnelling in the water-bearing moraine layer and keeping overburden to a minimum. This has led to the current position that fits tightly within the natural boundaries of the limestone formations, and the lake whose depth increases to the north-east.

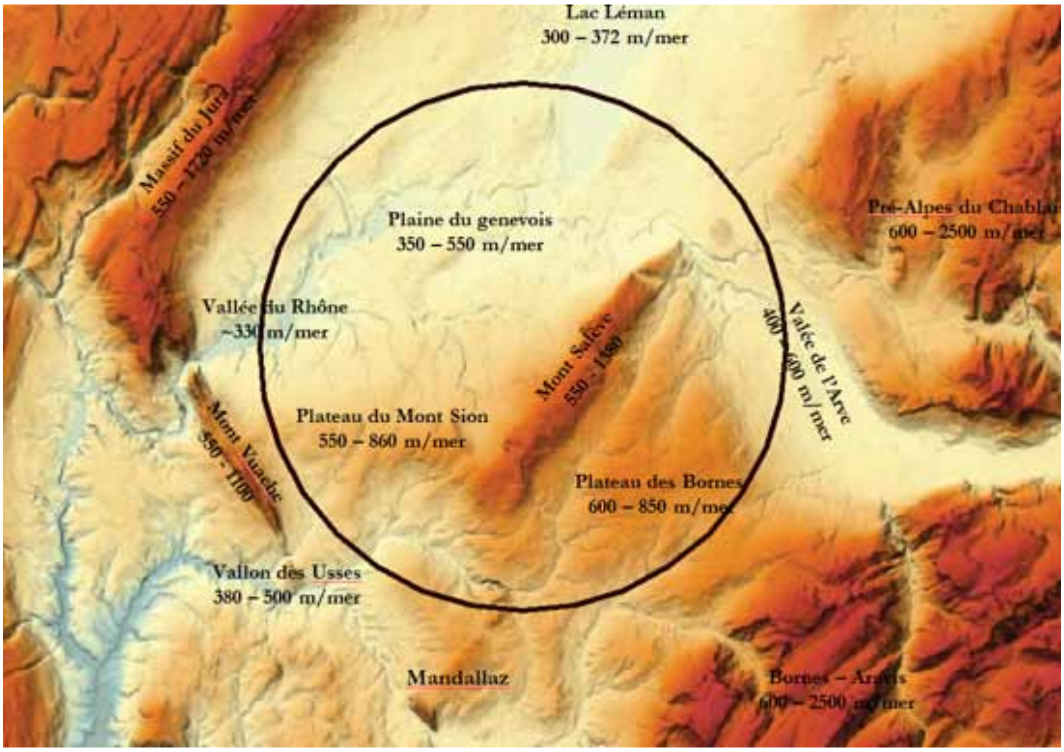

Figure 5.1: Optimum Placement of the FCC

6. VERTICAL ALIGNMENT

A key objective of the study so far has been to develop a ring vertical alignment that places all cavern excavations in rock and the remaining structures and connections in adequate ground conditions. These conditions tend to be met by deepening the vertical alignment. On the other hand, operation of the FCC and connections to the existing LHC are more efficient with a shallow alignment.

On the basis of the available information, the ring vertical alignment has been defined so that both conditions are satisfied in the best way. This has resulted in an alignment with tunnel ground covers of between 50 m and 600 m.

7. SHAFTS

In general there are two types of shaft depending on the internal diameter.

7.1. Large Shafts

Shafts in molasse have historically been built more cost effectively using mined construction with combination of shotcrete and rockbolts. This is still the logical solution for the FCC shafts with diameters between 10m and 18m.

The presence of water bearing moraines does not allow the use of conventional mining near the surface. Instead, other methods such as caissons, diaphragm walls or secant piles shall be used in combination with additional water control measures such as grouting and ground freezing.

An alternative technology that has been explored is the use of Vertical Sinking Machines (VSM). Extensive consultation has been carried out with VSM manufacturers in order to achieve better understanding of the technical constraints, advance rates and costs.

It is clear that it is necessary to balance site installation lead times against excavation rates in order to obtain the best solution. Table 7.1 states advantages and disadvantages for each of the methods.

Table 7.1: Methodologies for Shaft Sinking in Morraine

Method	Advantages	Disadvantages
Secant Piles	□ Quick site installation. □ Cost effective solution for shallow depths.	□ Large tolerances at depth. □ Risk of inadequate water control at depth. □ Ground water needs to be lowered as excavation progresses.
Diaphragm Walls	□ It is expected that technological advances will allow diaphragm walls of up to 100m when the project goes for construction. □ Relatively short lead times and site installations for shaft depths of up to 70m.	□ Large quantities of concrete compared to other methods. □ Verticality tolerances at depth. □ Ground water needs to be lowered as excavation progresses. □ Lead times extend to between 6 months and 8 months for deeper shafts.
VSM	□ Excavations are carried out 'wet' so there is minimal impact on the groundwater table. □ There are no personnel in the excavation which minimises H&S risks. □ One machine can be used for several shaft diameters. □ Advance rates are much higher than with other techniques in soft ground. □ Permanent lining can be installed as the excavation progresses.	□ Unless machines are available for hire, lead times would be around 9 months for purchase and site installation. □ Machine costs are high.

It is expected that shaft sections in moraine will eventually be built using several techniques as contractors will seek cost-effectiveness and risk reduction. At this stage, it is expected that most shafts can be built in moraine using either secant piling or diaphragm walling given the expected relatively shallow soft deposits. However, there is scope for using VSM machines for the Service Shafts between C and F.

7.2. Small Shafts

The project requires the construction of survey shafts. These are only 2m in diameter and shall connect the crown of the Machine Tunnels to ground surface. When applying standard tunnelling construction, shafts are typically built at some horizontal deviations that might be as large as 1m for every 200m of vertical excavation. The use of a pilot borehole using a guided system, which has similar specifications to those used in the oil industry, would be a suitable methodology. The pilot borehole will be the reference alignment for enlarging the excavation using one or a mixture of raise boring in molasse and one of the methods stated in Table 7.1 for moraine.

8. CAVERNS

The project includes caverns of different sizes and lengths. The 35m high, 35m span Experiment Caverns (Figure 8.1), that will host the collision detectors, are surely the most impressive structures to be built. In contrast with hydropower projects where large caverns are placed to suit the best joint orientation and ground conditions, these four caverns will need to be in predetermined locations.

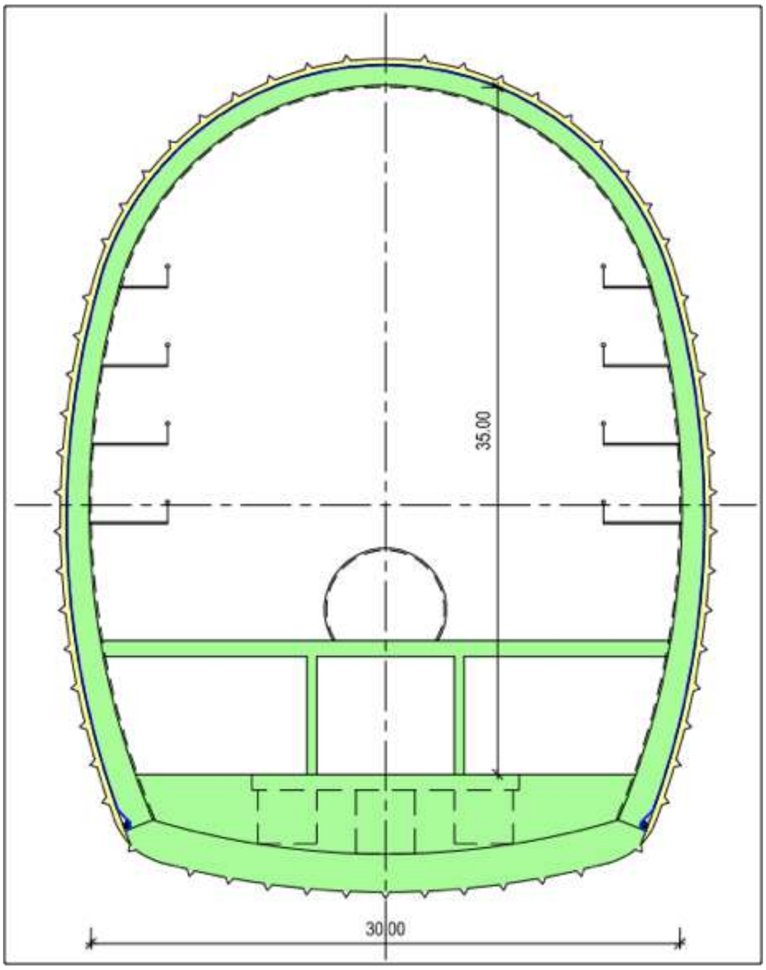

Figure 8.1: Experiment Cavern Cross Section

The 25m span Service Caverns will also be used to launch most of the TBMs. Some Junction Caverns have been adjusted in size to merge TBM drives to the Machine Tunnels using minimum turning radiuses of 400 m.

9. TUNNELS

The project has more than 140 km of tunnels with diameters of between 5m and 7m that will demand all available construction methodology. However, it is expected that most of these will be built using tunnel boring machines (TBM).

Figure 9.1 shows typical sections for the TBM and mined tunnels. The layout of the invert is planned so that the magnets are not subjected to any type of movements from long term ground creep. The sections also contain a fresh air duct in the invert and an exhaust duct for helium or smoke extraction.

Life safety is based on compartmentalisation of an incident by placing fire walls and doors at 400m spacing. In case of an accidental fire or gas release, the zone affected is isolated from the rest of the tunnel by immediate closure of the fire doors.

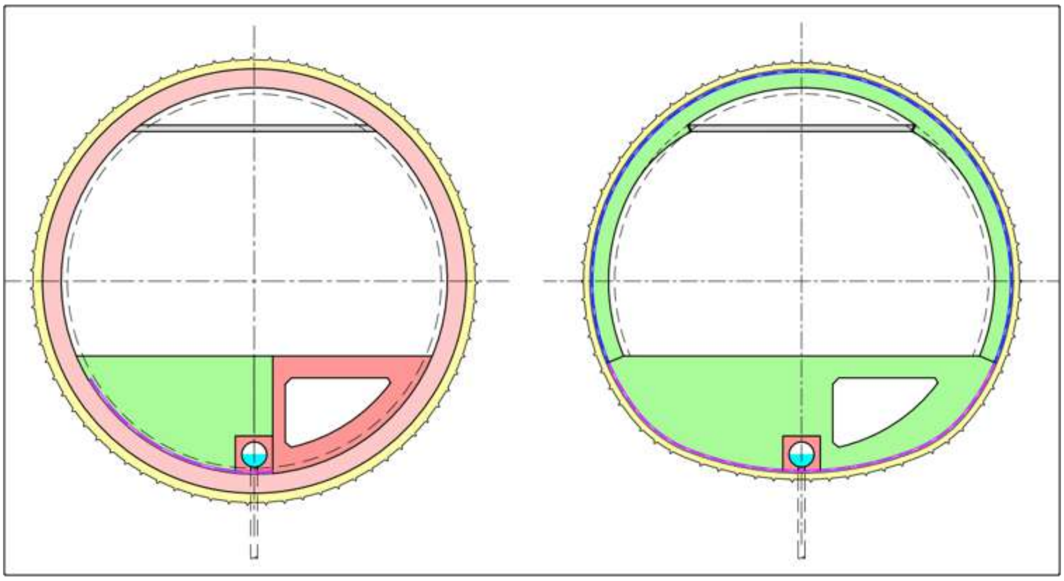

Figure 9.1: Typical Cross Sections for TBM and Mined Tunnels

Although the tunnel sizes are similar to those in metro projects, it is required to establish modern systems of work that allow sequential construction of permanent linings, inverts and internal structures in order to fulfil the required construction deliverable schedules.

The tunnel under Lake Geneva will be excavated in soft ground and with water pressures of up to 10 bar. This poses technical challenges for TBM technology and waterproofing gaskets.

Figure 9.2 shows an overview of the expected construction methods distribution between TBM and mined tunnels.

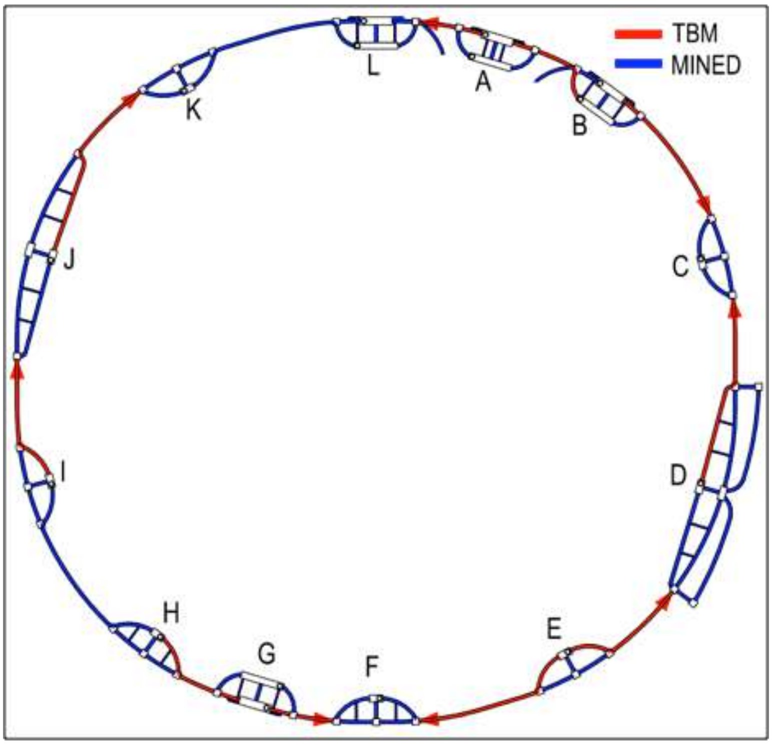

Figure 9.2: Proposed Tunnel Construction Methodology

10. COSTS CALCULATIONS

Underground construction costs are being calculated using detailed analyses that allow:

- Variation of the dimensions of the underground structures;
- Calculation of detailed quantities with varying ground conditions, tunnel support and construction methodology;
- Calculation of unit prices for 12 construction lots, which represent the basis for the future construction contracts;
- Changes in labour, materials, consumables and equipment costs;
- Modification of construction cost indexes for Switzerland and France;
- Calculation of the construction costs per unit, which allow comparisons with previous projects.

In addition to the above, the costs for project buildings are calculated using existing databases. The proposed buildings are compared to hundreds of recent project examples in order to select average unit costs that fit both with its structure type and final use.

The result of this stage is a comprehensive Cost Model, which can be used by CERN to calculate costs under different boundary conditions allowing variations as the project progresses.

11. SCHEDULE CALCULATIONS

In order to sequence the project, the works have been divided into 12 lots, which contain all the structures to be driven from a surface point. It is possible that these lots will correspond to the civil construction contracts.

A breakdown of activities was carried out for each lot. This breakdown is obtained assuming an initial sequence of events, which can be later adjusted to include the acquisition of plant for the whole project.

After defining the project lots, advance rates for each construction type were assumed. In order to determine the advance rates, the following reference data has been considered:

- Previous project experience;
- Bills of quantities;
- Ground conditions.

CERN needs to accelerate construction for two lots with at least three shafts in order to provide adequate lead way for installation of magnets and all other associated equipment. In order to achieve this, intermediate inclined access adits are planned. Digital landscape models were prepared including geological information and also environmental restrictions. Possible alignments were designed on the basis of the maximum adit gradient. Figure 11.1 shows calculated clouds of possible starting points for an adit driving to an intermediate starting point at Machine Tunnel level.

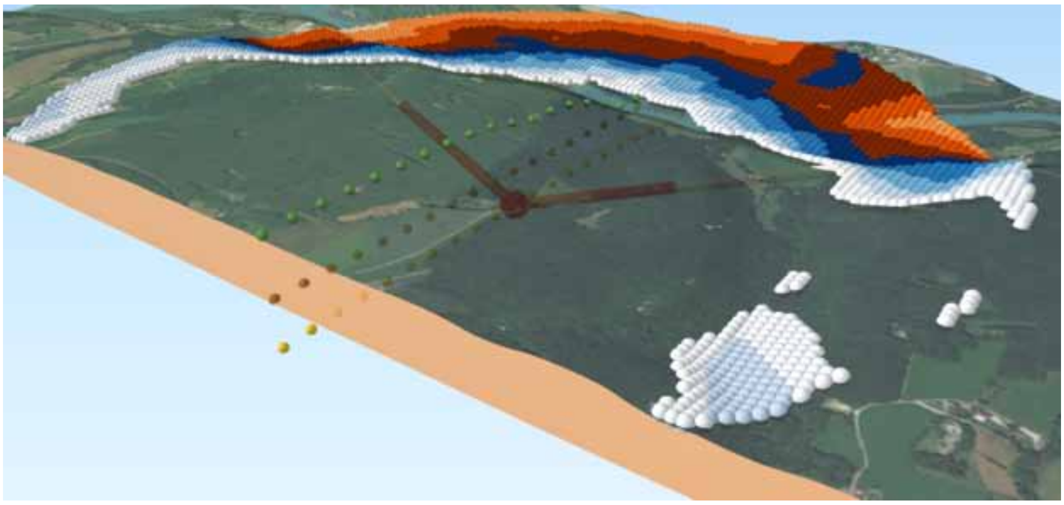

Figure 11.1: 3D-Model Showing Clouds of Possible Access Adit Points

12. CONCLUSIONS

The underground structures that will be built to host the Future Circular Collider form part of what will most probably be the biggest tunnelling project in the world when it goes for construction in 2026. Such undertaking poses serious planning and constructability challenges for which CERN is preparing with the support from ILF.

The project has been set out at the optimum location to achieve the best connections to the existing collider and within the most favourable and cost effective ground conditions. Some degree of modification is expected following the results from geological site investigations within the next design stages.

There is extensive tunnelling experience in the expected ground conditions available. While excavations in the deep molasse would be relatively dry and stable, shaft excavations in moraine will require adequate support and ground water control. In addition to this, limestone might release large water inflows which will have to be dealt with during construction and operation.

As the equipment to be kept in the tunnels and caverns is sensitive to very small movements and the operation of the project is different to that of a conventional infrastructure project, bespoke solutions are needed.

13. REFERENCES

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