The LHC-Project of CERN – Large Caverns in Soft Rock a Challenge for Scientists and Engineers

Hans-Christian Kurzweil

GEOCONSULT Consulting Engineers, Salzburg, Austria

ABSTRACT

CERN, the European Laboratory for Particle Physics, are upgrading their existing particle accelerator for the next generation of experiments and have three major packages of underground construction work in progress. Each package involves the construction of shafts, cavern, tunnels and surface buildings.
The LHC works at Point 5 include two large shafts, two major parallel caverns with a total span of 50 m, which are separated by a 7 m wide and 28 m high concrete pillar, and a system of secondary tunnels and caverns. The overburden ground consists of around 50 m of water bearing moraine (silty, clayey gravels and sands) overlying 20 m of molasse, which consists of horizontally bedded marls and sandstones. The shafts have been constructed with ground freezing, primary concrete lining, membrane and secondary slipformed concrete lining. The concrete pillar was then excavated and concreted in advance of excavation of the two caverns. Cavern construction includes primary support of shotcrete lining and rock bolts, followed by waterproof membrane and primary support and insitu concrete secondary lining.

1. INTRODUCTION AND PROJECT DESCRIPTION

The European Laboratory for Particle Physics (CERN) is the worlds largest research laboratory for particle physics. Founded in 1954, CERN is supported by 19 member states. The laboratory has over 2800 permanent staff and is used by more than 6500 scientists of worldwide 80 nationalities. The laboratory facilities themselves are located at the Franco-Swiss border adjacent to Geneva airport and include a series of linear and circular particle accelerators, which are hosted in tunnels in a depth between 50 and 100 m. The main Large Electron Positron (LEP) accelerator, which is operating since 1989, has a circumference of 26.7 km. Along the LEP, several access points and so-called experimental or detector points are located. At these experimental points, energy from particle collisions is measured in the so-called detectors, which are hosted in large underground caverns or cavern systems. The older Super Proton Synchrotron (SPS) has a circumference of 6.9 km and is connected to the LEP at experimental Point 1.

In late 2000, CERN have shut down their existing particle accelerator, the Large Electron Positron (LEP) and have processed to dismantle the old LEP machine. After finalisation of underground civil works in late 2003 the existing system will be replaced by the Large Hadron Collider (LHC) machine, which shall start its operation in 2005. The LHC will use all existing LEP underground structures but will also require substantial new surface and underground facilities as shown in figure 1. The two new detectors, the ATLAS at Point 1 and the Compact Muon Solenoid (CMS) at Point 5, will be larger and more complex than any built to date. The new detectors, weighing up to 15,000 tons, will be installed in newly built caverns. To be able to keep the relatively tight time schedule, the detectors will be preassembled in the surface work shop buildings to pieces up to 2000 tons and will then be descended through the shafts down to the caverns, where final installation is done.

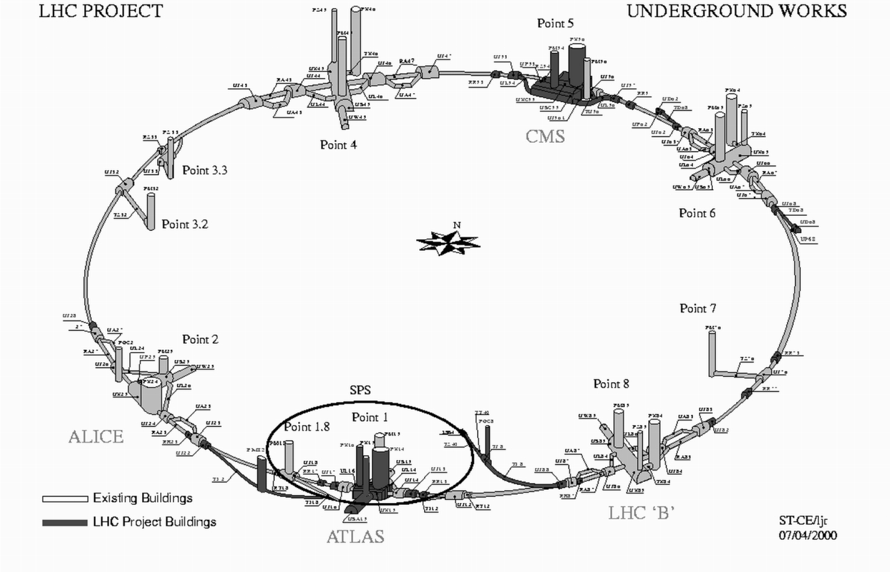

Figure 1 – Layout of the LEP tunnel and future LHC structures

Structural upgrading for the new Large Hadron Collider LHC is divided into three major packages of civil works. Each package involves design and construction of shafts, caverns, tunnels and surface buildings. In early 1996 an Anglo-Swiss-Austrian JV consisting of three companies, Jacobs Gibb (GB) - SGI Ingenierie (Switzerland) - Geoconsult (A) was awarded the contract for civil engineering consultancy services for one of these packages, the Compact Muon Solenoid (CMS) structures at Point 5, which is shown in figure 2. SGI was in charge of the design for the surface buildings, Jacobs GIBB for shafts and project management and Geoconsult for all remaining underground structures like caverns and tunnels. The contract comprised preliminary, tender and detail design and construction supervision as Engineer.

Figure 2 – The CMS in the assembling stage

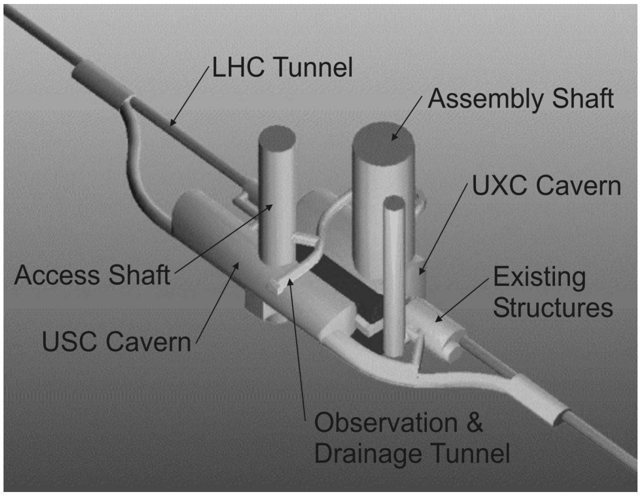

Figure 3 – Underground structures at experimental Point 5

2. CIVIL WORKS FOR THE LARGE HADRON COLLIDER AT POINT 5

Point 5, mainly consists of two large parallel caverns, which are separated by a massive concrete pillar. The caverns are connected to the surface by two large diameter shafts. Figure 3 shows a model of Point 5 underground structures. Experimental Cavern UXC 55, which will later host the 15,000 tons CMS-Detector has a width of 27 m, a height of 34 m and a length of 53 m. The parallel-located Service Cavern USC 55 will later, among lots of other equipment, host the extensive computer site for control and evaluation of experiments. It has a width of 19 m, a height of 17 m and a length of 85 m. To reduce the total lengths of optical cables, required for data transfer between Experimental and Service cavern, it was a requirement by CERN to keep the distance between the two caverns to an absolute minimum, representing a major cost factor. Due to the total span of the cavern complex of more than 50 m a massive concrete pillar of 7 m width had to be designed to support loads induced by the wide spanned rock canopy.

Each of the caverns is connected to the surface by a central shaft in the cavern roof. The permanent access shaft above the Service cavern has a diameter of 12 m. The ventilation and detector installation shaft above the experimental cavern has a diameter of 21 m. The size of this shaft is guided by requirements of the largest size of detector rings, which will be pre-assembled at the surface and then descended down the shaft into the cavern in parts of up to 2000 tons.

Remaining elements of Point 5 consist of several smaller service caverns, access and connection tunnels and galleries for monitoring and measuring purposes - utilised during construction as well as for the operational phase.

3. GEOLOGY

The CERN site is located within the Geneva Basin. The Geneva Basin is underlain by crystalline basement rocks and formations of the Triassic, Jurassic and Cretaceous ages and is filled with sedimentary deposits, the so-called Molasse, which again is overlain by Quaternary glacial moraines. The Molasse of the Geneva Basin comprises horizontally bedded sedimentary deposit layers of marls, limestones, sandstones, sandy marls and marly sandstones with varying strengths, material properties and layer thickness. The moraine deposits comprise essentially gravels and sands with varying amounts of silt and clay. Figure 4 shows the geological layers at Point 5 caverns location.

The existing LEP tunnel is located predominantly within the molasse, at depths between 50 and 100 m below ground surface. The thickness of the overlaying moraine layer varies along the project from approximately 5 to 50 m. The water table is generally a few meters below ground level representing an aquifer for local ground water supply.

At point 5 total rock cover above cavern roofs is approximately 70 m, consisting of 50 m of water-bearing glacial moraine, followed by approximately 20 m of Molasse directly above cavern roofs. A special challenge for design and construction represents an 8 m thick weakness zone, which is located more or less directly above cavern roofs, consisting of so-called ‘marl grumeleuse’ and ‘marl laminated’ layers, which have a relatively low strength, a quite high creep capacity and are prone to swelling if in contact with water. A similar ‘weak layer’ is located directly below the invert of the experimental cavern UXC 55, challenging foundation design.

Close proximity of the waterbearing moraine layer to swelling-sensitive weak layers in cavern roofs represented one of the most challenging issues for cavern design.

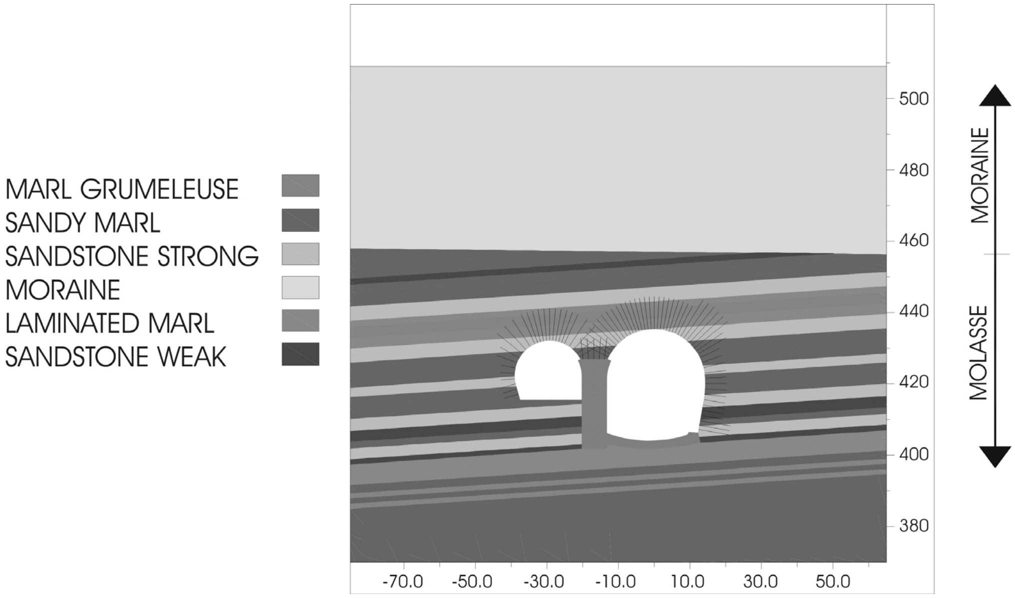

Figure 4 – Two-dimensional UDEC model with geotechnical layers

4. DESIGN OF POINT 5 STRUCTURES

4.1 Key issues for main cavern design

For the design of the main cavern system several key issues were identified and had to be addressed by the design as listed below:

- Low cover of competent rock of only 20 m to waterbearing moraine in combination with wide span of main cavern complex of more than 50 m.
- Only limited displacements in rock mass allowed to avoid water ingress from moraine
- Weak rock layers above cavern roof and below invert prone to creeping and swelling
- Limited precedence of a cavern system of this size in this type of soft rock
- Three-dimensional situation of shaft and cavern layout
- Close proximity to existing structures (one cavern and one shaft, see figure 3)
- Complex long term behaviour and material parameters of rock mass
- CERN’s requirement of a completely watertight secondary lining
- CERN’s strict requirements on layout due to their scientific equipment constraints
- CERN’s requirement to maintain operation of existing LEP machine during first phase of underground constructions and accompanying restrictions to displacements and vibrations during this construction phase

4.2 Design methodology

Dimensions of the new LHC cavern system exceed those of previously constructed LEP structures and takes the new design beyond previous precedent. To achieve a safe and economical design of underground structures it was necessary to gain a fundamental understanding of geotechnical properties of the molasse and its sensitivity to proposed excavation sequences and rock support measures. Consequently, design methodology was based on a representative characterisation and an adequate modelling of the molasse.

The design process involved fundamental analytical and two- and three-dimensional numerical calculation models which considered the specific properties of the rock mass for various short term load cases during construction stage as well as for characteristic long term load cases like creeping and swelling.

For the numerical design calculations a typical two-dimensional cross section was selected across the cavern system (see figure 4 above) which was modelled with the distinct element code UDEC. This allowed a detailed modelling of the various geotechnical layers of the molasse and consequently provided a valuable tool for analysis and evaluation of behaviour of the complex interaction between rock mass and cavern system. To consider the highly three-dimensional character of the cavern and shaft structures, including secondary concrete lining, three-dimensional calculations were performed with the boundary element code BEFE. Figure 5 shows the three-dimensional BEFE model.

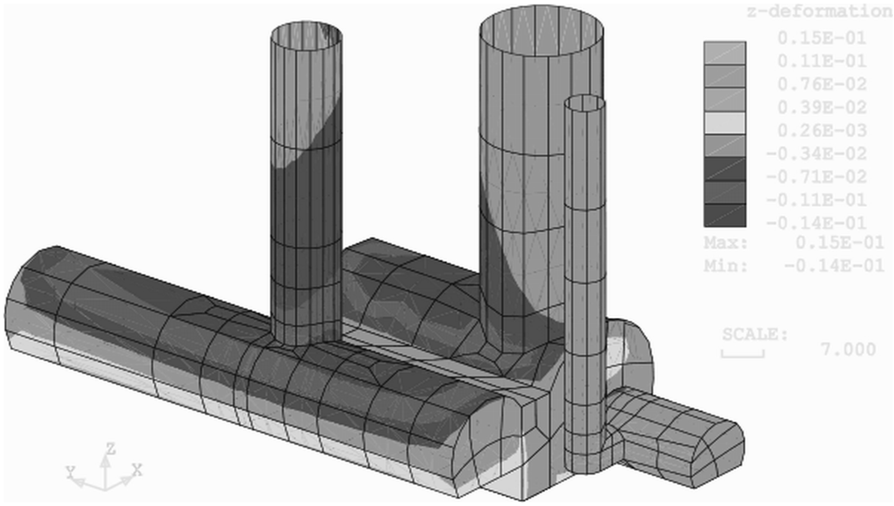

Figure 5 – Three-dimensional BEFE calculation model

Due to software and computer capacity limits, it was not possible with the three-dimensional calculation model to do a detailed modelling of the complex geotechnical features and load cases as it was done for the two-dimensional UDEC model. Nevertheless, to be able to simulate a realistic rock mass behaviour also with the three-dimensional model, the simplified three-dimensional model was calibrated to the more accurate two-dimensional model, considering all decisive load cases both for short term and long term conditions, such as creeping and swelling. The various numerical calculations were complemented by analysis of possible failure scenarios and modes.

Short term input parameters for the numerical calculations were derived from site investigation data. However, for the long term load cases complex interactions between stress-strain state and time history, water content, swelling and creeping properties exist and the numerous input parameters, necessary for the respective time-dependent material constitutive laws, could not be satisfactory determined by the site investigation program and tests. Consequently, design for the long term load cases was based on the common approach of adopting reduced strength and stiffness parameters to simulate creeping. Modelling of swelling was simplified by applying an equivalent thermal change in those rock mass layers, which were subject to swelling. Amount of temperature applied to ‘swelling layers’ was calibrated to swelling tests performed within the site investigation program and testing.

5. CONSTRUCTION METHODS AND ROCK SUPPORT

Shafts were sunk through the upper 50 m of waterbearing moraine utilising ground freezing for shaft wall support and ground water control. Shafts were excavated sequentially down and primary concrete rings were cast progressively to form a 1–1.4 m thick primary lining ring. Below the moraine within the molasse, fibre-reinforced shotcrete and rock bolts were used for primary support. Once shaft excavation was completed and the primary lining ring was in place, a secondary 80 cm thick concrete lining was slip formed from shaft bottom up, separated from the primary lining by a plastic membrane with fleece backing. A major requirement to shaft construction was that no water ingress from the moraine into the molasse is initiated by construction. Consequently, the shafts had to be sealed off at the transition moraine / molasse by an extensive grouting operation, creating a tight grout plug around the shafts.

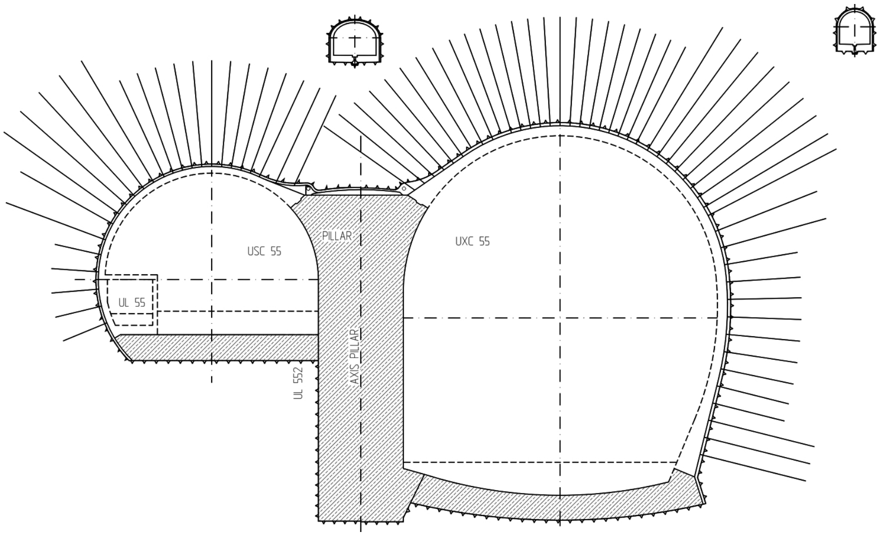

Figure 6 – Cavern cross section with typical rock support

The cavern system was excavated, starting from the service cavern ‘access’ shaft, with advance excavation of the central pillar by sequential top-down operation and subsequent concrete backfilling of the pillar. After concrete pillar construction was completed, the caverns were excavated by road headers. The caverns were excavated with top heading and 2 to 4 benches plus invert, depending on the height of the caverns. Primary support consists of 30 to 50 cm fibre-reinforced shotcrete and systematic, fully grouted rock bolts with up to 12 m length. Typical rock support for the main caverns is shown in figure 6. The floors of the main caverns are formed by a massive concrete invert arch to provide a stiff foundation for the caverns, which may resist against swelling pressures from the rock mass below. The three-dimensional transition from shafts to cavern roofs is additionally supported by a shotcrete collar, and anchored back into the rock mass with pretensioned high load rock anchors.

The reinforced secondary concrete lining has a thickness of 80 cm in the Experimental and 50 cm in the Service Cavern. As water ingress is a sensitive issue and no hydrostatic water pressure is allowed to build up behind the linings, water tightness of the whole cavern complex including the pillar will be achieved by a plastic membrane with fleece backing, which is connected to the extensive drainage system designed around the whole cavern complex.

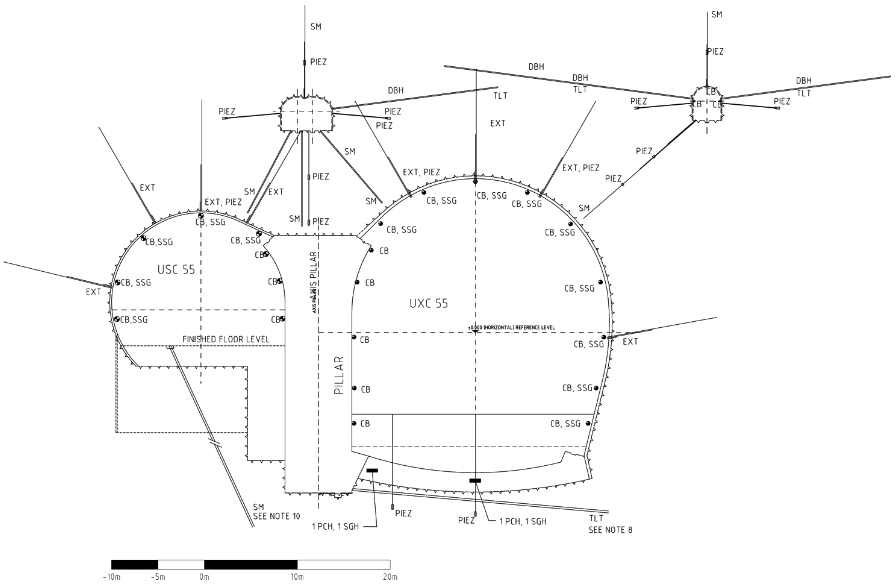

Figure 7 – Typical monitoring section

For construction supervision and design verification an extensive instrumentation and monitoring program was established, which essentially comprised 14 optical targets per monitoring section for optical free stationed absolute 3D displacement measurements, radial extensometers, tiltmeters, shotcrete strain meters, radial pressure cells and piezometers. Monitoring sections as shown in figure 7 were placed in the caverns at distances of 10 m. In advance of cavern excavation an 'Observation and Drainage Gallery' was constructed above the future cavern roofs, which gave the opportunity to observe rock mass behaviour from the very beginning of cavern construction by various monitoring instruments installed. It further gave the possibility to detect and drain ground water ingress from the moraine before water pressure can built up above cavern roofs. Finally, in case of adverse rock mass behaviour additional contingency rock support measures could be installed from the gallery.

6. CONSTRUCTION PROGRESS AND DESIGN REVIEW DURING CONSTRUCTION

In late 2000 during pillar excavation which created an opening of 54 m length, 8 m width and 28 m height, monitoring results from the optical 3D displacement and multi-rod extensometer measurements revealed more pronounced time-dependent displacements in the rock mass than originally expected. As described above, this time dependency was principally known and addressed in the initial design. However, monitoring results during pillar excavation provided additional information on actual elastic and time-dependent behaviour of the molasse initiated by the big size excavation. Logged geology and monitoring results from pillar excavation were consequently used for back-analysis and review of the initial design. Now, with actual information on time-dependent properties and geology available, it was possible to calibrate a more sophisticated time-dependent material constitutive law for the numerical calculation models. However, data provided by pillar excavation could only reflect the relatively short construction period of eight month for pillar excavation. Consequently, long term behaviour, which is decisive for secondary lining design, had to be extrapolated from available data. Back-analysis of pillar excavation resulted in two extrapolated trend lines for long-term time-dependent displacements – an optimistic and a pessimistic trend line.

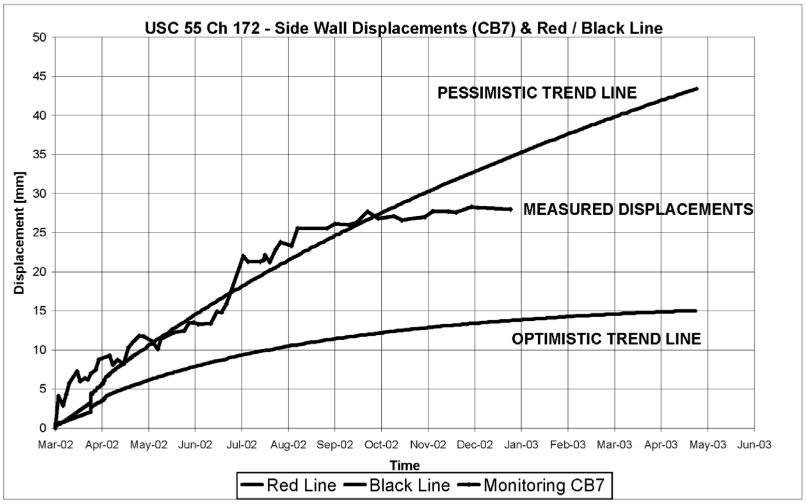

Figure 8 – Predicted trend lines and measured displacement curves

Based on the results from pillar back-analysis, optimistic and pessimistic long term displacement trend lines were developed in the subsequent cavern design review. The displacement trend lines for the caverns are shown in figure 8. An upgrading of the initial design was required, involving thicker shotcrete lining and stronger rock bolts for primary support, and higher concrete quality and locally additional reinforcement for secondary concrete lining.

7. CONCLUSION

After finalisation of excavation works and concreting of cavern inverts, results from construction monitoring show that behaviour of caverns is within predictions of the design review calculations. Displacement values and trends are, as illustrated in figure 8, between the two predicted - pessimistic and optimistic – trend lines and verify the stability of the structure and the adequacy of secondary lining design for long term loads.

Figures 9 & 10 – Construction of experimental cavern UXC 55