WORLD TUNNELLING

Roughcastle Tunnel above an old mine

Construction of the 147m long Roughcastle Tunnel, part of the Millennium Link connecting the Forth and Clyde canal and the Union canal at Falkirk, Scotland, provided an unusual challenge for designer and contractor alike. It overlays an unfilled, abandoned stoop-and-pillar fireclay mine at shallow depth.

Boreholes were drilled into the mine to ascertain the rock quality in the roof and pillars, and ultrasonic surveys carried out to determine the condition of the workings to assess the risk, and the possible effect on the tunnel, of a mine collapse during the tunnel's 120 year design life.

The tunnel was successfully completed using a single pass sprayed concrete lining technique in a mixed face of stiff glacial till overlying Lower Coal Measures comprising interbedded sandstones, mudstones and coals.

British Waterways (Scotland) awarded the contract, known as Falkirk Interchange, Millennium Link, Contract 6, to a joint venture between Morrison Construction Ltd and Bachy Soletanche Ltd. The tunnel was subcontracted to Shotcrete Ltd (formerly Spray Concrete Ltd) as a design and build package. High-Point Rendel provided the tunnel design as consultant to Shotcrete Ltd.

The 7m wide tunnel, incorporating a 2m wide towpath, also passes beneath the Roman Antonine Wall dating from AD142 which is a site of archaeological importance. It also passes under a more modern form of transport, the Glasgow to Edinburgh railway.

Initial proposals for the canal incorporated a tunnel beneath the railway; but a cut-and-cover bridge was eventually put in place by British Waterways, with First Engineering as design-and-build contractor. This was carried out in advance of the main contract to suit the timing of the introduction of a new fast rail service between Glasgow and Edinburgh. The bridge formed the tunnel portal at the southern end of the tunnel.

Abandoned mines

The abandoned Roughcastle Mine was worked up until 1980 with the stoop-and-room workings lying at a depth of between 10 and 18m below the tunnel invert (Figure 1). Beneath the line of the tunnel a main haulage road runs approximately east-west with interconnecting gates running off to the north and south. The mine in the vicinity of the tunnel is flooded.

Tunnel construction showing the side drift technique with special access equipment for support installation (left) and the Schaeff excavator from Specialist Plant (right)

A preliminary assessment of the risks posed, both during and after construction, was undertaken using data from the mine abandonment plan and a preliminary risk model was developed. This concluded that, based upon a conservative review of the data, the potential room heights, widths and junction configurations, considered with the weak nature of the mudstone elements of the Lower Coal Measures strata, conditions were such that a high risk of roof beam failure existed. Due to the size of the mine stoops, pillar failure was not considered to be a significant risk factor.

Roof beam failure could initiate significant chimney migration, which could pose a risk to the tunnel in two principal ways:

(1) If chimney migration was already active – by disruption of tunnel construction operations if a chimney was encountered within the face or if one was located beneath the working floor;

(2) Future chimney migration could seriously compromise the integrity of the completed tunnel structure with potentially significant safety consequence to tunnel users.

Further investigation comprised the drilling of five boreholes of which four penetrated the flooded mine cavity.

The cavities penetrated were subjected to ultrasonic surveying in an attempt to determine their size and condition. Although the surveys provided detail on shape and condition, room orientation was difficult to determine. It is believed that metallic equipment was left in the mine on abandonment and the equipment produced a magnetic deviation on the ultrasonic survey scans. Orientation during surveying was therefore difficult and it was necessary to undertake an office-based manipulation of the data using dedicated computer software and overlays.

The results of the investigation indicated that the mine was in good condition with no signs of roof collapse. It was flooded with a main roadway height of about 4m and general room heights of 2.5m.

Both qualitative and quantitative risk assessment models indicated that the risk of beam failure and collapse-chimney initiation in sandstone or siltstone was extremely low based upon current conditions. The percentage of sandstone and siltstone to other rock types was therefore calculated in the

Erecting the lattice arches and wire mesh prior to shotcreting using specially made access equipment

stratigraphic sequence between the base of the proposed tunnel and the mine roof. In general the percentage decreased from north to south along the tunnel route from a maximum of 80% to a minimum of 42%. The actual risk of a collapse chimney migrating to the base of the tunnel was considered therefore to be lower than that suggested by a consideration of mudstone roof beams alone, in the short-to-medium term at least.

Consequently the risk assessments led to the conclusions that:

(1) a roof collapse could result in a collapse feature of between 5m and 7m in diameter at tunnel level. However, although the consequences of such could be severe, due to the apparent low age of the mine the risk of encountering such a feature was assessed as low;

(2) a migrating collapse-chimney reaching the completed tunnel could result in the failure of the tunnel lining. In order to reduce the risk to the completed structure the following actions were undertaken and recommendations made:

(a) The effects and consequences on tunnel design were considered, in particular the effect of a collapse occurring beneath the completed tunnel invert. The option for strengthening the tunnel invert to bridge potential collapses was initiated and the effect of a collapse running up the outside of the tunnel lining was analysed.

(b) Mitigation measures form an essential part of a long-term tunnel management strategy, in the form of tunnel monitoring and potentially monitoring of the mine-workings. Such measures may include tomography using cross-hole velocity surveys, tomography using low frequency reflection seismic signals, extensometers installed in the roof strata and precise levelling along the tunnel length.

Design development

Shotcrete Ltd developed the design based on the New Austrian Tunnelling Method (NATM) technology and a 'one-pass' sprayed concrete lining. Unlike traditional tunnels constructed using NATM, this tunnel was being driven through a mixed stratum, with the crown positioned within glacial till throughout the drive. The invert, however, was to be constructed within the sandstone for its full length. This meant that unlike the traditional NATM tunnel, which has a curved invert, the Roughcastle Tunnel could be built with a horizontal invert.

The tunnel construction team also endeavoured to develop the most efficient excavation sequence before meeting their designers to ensure that their proposals would work. This contractor-led approach meant that the most efficient and cost effective design was produced, but always with a strong sense of 'buildability'.

On this basis the tunnel designer finalised the design of the tunnel and northern portal. For reasons of safety, and to ensure maximum efficiency, it was decided to advance the tunnel using the side drift technique, with a temporary sidewall, 120mm thick, to ensure the stability of the left drift. Although this system is generally used to increase stability and reduce face loss, its primary use on this project was to split the tunnel face into two separate work cells, allowing both excavation and construction activities to operate concurrently.

The temporary invert level was kept as high as possible to reduce the amount of rock excavation during the heading construction. However, the heading had to accommodate the self-loading mixers, which were the largest items of plant entering the tunnel during construction. There had to be enough space to allow the mixers and spoil removal vehicles to pass within the tunnel.

The tunnel portal with shotcreting complete on a reinforced structure with soil nails

Mix design

On completion of the design and tunnelling sequences, the mix design could be formulated. It is essential that the mix design is not finalised until the tunnelling cycle times have been calculated as this could lead to a cocktail of unnecessary admixtures being added to the mix. The key to the cohesive and plastic properties of the shotcrete material is the development of the paste which, in the wet process, enables the transportation of the shotcrete within the lines without bleeding or clogging, and helps to prevent segregation during the spraying process. The shotcrete mix used on this project was batched on site using self-loading transit mixers, allowing the shotcrete to be batched on demand and transported into the tunnel within the same vehicle.

With soft rock linings the shell is subject to immediate load, and therefore the concrete material is being stressed and deformed during a very critical period of its life, whereas the most important aspect of any concrete shell is the ability of the concrete to take compressive stress. Reinforcement encapsulation, day joints and concrete density are also important and must be addressed if longevity is a consideration. From the sprayed concrete practitioner's viewpoint, *in situ* quality is dependent on mix design, together with the suitability and set up of the key equipment and the expertise in the actual placement. These factors cannot satisfactorily be isolated and must be combined with three fundamental mix design/placement criteria:

(1) An intimate bond (contact coat) must be achieved to enable safe build-out on the substrate. If an adequate bond cannot be achieved, the concrete will tend to 'hang' from reinforcement giving rise to poor encapsulation and voiding.

(2) The mix must be designed to give an appropriate early strength development, not just to accommodate early ground stresses and allow the ground to yield, but to enable the safe progress of the work during the following shift.

(3) For permanent support, the concrete must reliably achieve the designer's long term performance requirement, which may include a degree of watertightness and a smooth internal finish as well as minimum strength criteria.

Portal construction

Work began with the construction of the North Portal. The portal was designed to look traditional and was 'horseshoe' shape. A reinforced sprayed concrete structure, it was restrained by 20m-long soil nails into the hillside. The portal was built top-down in six 2-m benches; the soil nails were installed on each bench and immediately covered with two layers of reinforcement and 200mm of sprayed concrete. The next bench was then constructed in the same order.

A plug of unexcavated material supported the tunnel eye. A 500mm x 500mm reinforced sprayed concrete beam was then installed. Prior to the construction of the beam, spiles were driven into the ground along the line of the tunnel at 500-mm centres to provide heading protection. The ends of these were then incorporated into the ring beam.

Unusual view through the base of sheet piles at the end of the tunnel excavation

Tunnel construction

Initially, the left side of the heading was advanced twice for one right-hand advance using a Schaeff 111 backhoe excavator. Once the left heading was 15m further advanced than the right side, the excavation and construction activities were carried out simultaneously. Spiles were installed on every advance at 1-m centres, even when the ground was stable. The reason for this was that the spiles were not only for heading support but also for advanced warning of obstructions (boulders) or voids from possible mine collapse. On two occasions the spiles were unable to be driven to their full depth and mapped out the position of boulders located in the crown. These could then be removed by careful excavation and dropped onto the tunnel floor. The largest boulder encountered was approximately 1.8m long and 1.5m in diameter.

On completion of the excavation, the excavator was moved to the other face to start the mucking cycle again. A purpose-built access machine was used to install the lattice arch and rear mesh. On completion of the cycle, this was then moved back to allow a 3-t excavator to pass and install spiles using a modified hydraulic breaker, passing through the lattice arch. The access machine was then repositioned, the second layer of reinforcement installed, and the shotcrete placed.

The shotcrete pump was positioned 5m back from the right-hand face, thus allowing traffic to pass to both faces. The shotcrete was all applied manually ensuring complete encapsulation of all reinforcement and arches. On completion of the shotcreting, the access machine was removed and positioned ready to commence on the opposite side once the excavation was complete.

The heading terminated at a line of sheet piles which had been installed prior to the new rail bridge construction. The piles were burnt out to the extrados of the tunnel lining and a reinforced ring beam constructed to carry the dead weight of the piles.

For the bench excavation, the removal of the rock was originally planned using backhoe excavators and hydraulic breakers. However, during the heading construction, an option of removing the centre section of the bench was reviewed and approved. A 50-t Wirtgen road planer removed the bench rock in strips varying in depth between 50mm and 150mm. (*World Tunnelling* September 2001 pp337-339) 1.5m of bench was left in place each side of the tunnel; the road planer then removed the centre section leaving the sides cut at an angle of 90°. The sides were later broken back using hydraulic breakers. The reinforcement and mesh was installed along with the floor slab starter bars, followed by the shotcrete.

The floor slab construction consisted of two heavily reinforced beams each side of the tunnel. These were 500mm deep and 1200mm wide and two layers of fabric reinforcement completed the floor structure spanning the tunnel width positioned above and below the cages. Finally, the lower walls of the tunnel were profiled to provide a 300mm bearing or shelf to carry the towpath structure and a PVC liner installed and covered with 100mm of polypropylene reinforced shotcrete to protect it from damage.

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Unique Millennium engineering

Also part of the £78 million ($ million) Millennium Link project is the Falkirk Wheel near the Roughcastle Tunnel. Although nothing to do with tunnelling (except for some of the participating companies), it is worth a mention here for the interest of engineers in general.

Opened on 24th May by the Queen as part of the Golden Jubilee Tour. The Falkirk Wheel is not only of unique design; it is the world's first rotating boat lift. The same function is normally performed by series of locks or by other special structures. The Wheel itself replaces as series of 11 locks that fell into disrepair in the 1930s.

The Falkirk Wheel connects a vertical gap of about 32 metres between two canals. It measures 35 metres in diameter on an axle of 28-metre length. It simultaneously lifts and lowers two 22m-long caissons that can each hold a payload of 300 tonnes (up to four boats on water).

Artist's impression of the completed Falkirk Wheel (Photo: British Waterways)

Originally conceived as a giant Ferris wheel carrying gondolas, the design as constructed was developed over many years. It features large, double-row, spherical roller bearings from SKF within specially designed housings to support the wheel. The design team was led by the Morrison/Bachy Soletanche joint venture (see main article) following the initial design by architects Nicoll Russel Studios of Dundee and exemplar designs by Binnie Black & Veatch.

Butterley Engineering of Ripley, Derbyshire, won the contract to build the wheel with engineering design consultant Bennett Associates, well known to the tunnelling industry. In conjunction with these companies, SKF developed a bearing design using a pair of purpose-designed, 4m-diameter, 3-row, slewing bearings; one positioned at either end of the wheel, with the outer rings bolted to the support structure and inner rings bolted to the arms. The inner ring carries gear teeth to transmit the drive to the wheel.

The Falkirk Wheel turns at a rate of 0.125 rev/min, moving boats at 4m/min on average. Thus a half turn is completed about once every 15 minutes, allowing for boat loading time.