Light at the end of the tunnel

A rail and road tunnel project in Karlsruhe, Germany, called for a complex grouting programme

Karlsruhe, the second-largest city in the state of Baden-Württemberg, in southwest Germany, near the Franco-German border, was one of the first cities to develop and implement a hybrid tram-train system, which consists of tram/light rail trains and commuter/regional rail trains running on the same set of tracks, thus enabling passengers to travel from surrounding towns directly into the heart of the city, without having to change lines.

This system, known as the Karlsruhe model, has led to the creation of similar tram-train systems in other locations in Germany and worldwide.

However, this convenience comes at a cost: the tram-trains travel down Kaiserstraße, a shopping boulevard in the city centre, at a rate of one per minute.

The increasing passenger numbers required new infrastructure in order to relieve the surface tram line on the central corridor along Kaiserstraße and to make the inner city more sustainable, pedestrian-friendly and attractive. At a referendum in 2002, the population of Karlsruhe voted for a combined rail and road tunnel project, known as the 'combined solution' (German: 'Kombilösung'), aimed to partially transfer underground the mostly above-ground tram-train network and to separate tram tracks from car and pedestrian traffic.

The Comacchio drill rigs MC 1200 and MC 22 performing vertical and inclined drilling from the Karl-Friedrich-Straße

PROJECT PHASES

The ground-breaking ceremony for the project was held in early 2010. Since then, the life of the inner city has been impacted by construction sites and route diversions, although a combination of state-of-the-art tunnel-boring technology and cut-and-cover construction methods were adopted by the designers in order to reduce the time required for above-ground construction.

The project includes several phases:

- The construction of a two-track rail tunnel (so called 'Stadtbahntunnel') in the east-west direction under the Kaiserstraße between Durlacher Tor and Mühlburger Tor (length: 2.4 km), with a branch tunnel (so called 'Südabzweig' or 'south junction') for south-bound lines from Marktplatz to Augartenstraße (length: 1 km) and a total of seven underground stops.
- Later in 2019, the construction of a two-track tram line in Kriegsstraße between Karlstor and Mendelssohnplatz, about 400m south of Kaiserstraße (length of tram line: 1.4 km) and the construction of a road tunnel under Kriegsstraße (length of road tunnel: 1.4 km).
- The dismantling of the surface tram tracks in Kaiserstraße between Europaplatz and Kronenplatz and in Karl-Friedrich-Straße/Ettlinger Straße between Marktplatz and Vierortbad, creating a rail-free pedestrian zone above ground.

The construction work was carried out by a joint venture of German Be-Mo Tunneling and Spanish Fomento de Construcciones y Contratas (FCC). The first phase of the project, comprising the Stadtbahntunnel and Südabzweig, started in 2010 and is scheduled to be completed this year.

The big breakthrough was made on September 7, 2015, as the 85m long and more than 1,200t heavy hydro-shield 'Giulia' completed the 2,050m-long excavation that goes from Durchlacher Alee to Mühlbuger Tor, after 10 months of work. With the excavation work under the cover of the future underground stations of the Stadtbahntunnel in progress, the construction of a second tunnel began at the end of January 2016, marking another milestone in the completion of the Kombilösung.

The 250m-long tunnel under Karl-Friedrich-Straße, going from Markplatz to Ettlinger Tor, due to the short distance and shallow depth, will be excavated full face according to the conventional New Austrian Tunnelling method (NATM). To counteract the groundwater lying completely above the tunnel and to prevent flooding of the excavation profile, the excavation is carried out using compressed air. In the working chamber - the area where the excavation work is carried out - the air pressure is currently 0.8bar (this corresponds to the pressure, to which a diver is exposed in 8m of water). Before excavation could start, a complex grouting programme was set up

to reduce compressed air losses and dangerous blow-outs during NATM excavation. The permeability of the subsoil on a 2m-thick crown around the excavation area needed to be reduced in order not to exceed the limit of $1x10^{-7}$m/sec. To obtain this, the use of low-pressure grouting had been envisaged by the designer. The permeation grouting was started in the autumn of 2014 by Rodio Spezialtiefbau, working as a subcontractor of BeMo/FCC.

SOIL CONDITIONS

The project area, located in the high banks of the Rhine river, is formed by an alternation of coarse permeable Quaternary gravels and sand layers, with cohesive, 1m to 1.5m-thick silt interlayers located closer to the tunnel elevation.

The design study of soil permeability and radius of influence of the grouts specified a drill pattern of 1.30m x 1.20m, measured at the deepest injection point. The little overburden separating the tunnel's crown and the road surface included a more than 100-year-old sewer and a dense network of underground services that was partially displaced. To avoid damages to the underground pipes and cables, PVC guide tubes were installed prior to drilling.

DRILLING

PVC tube à manchettes (TAMs) are used to provide access for grout injection. The boreholes are drilled vertically and inclined from the Karl-Friedrich-Straße. The project requirements include over 3,000 boreholes, for a total drilling length in excess of nearly 50,000m. Two Comacchio drill rigs are being used to perform the drillings: one MC22 and one MC1200, both equipped with a twin rod rack.

Drillings are made by the rotary method, using water or cement grout as flushing means. To increase the feed stroke and speed up production, special extensions were mounted on the 12m-long masts of the machines, reaching a drilling depth of 23m. The R3000 rotary head, designed by Comacchio, providing 2,400daNm torque, was equipped with a hydraulic chuck and special inserts of 101mm to handle the drill rods. After drilling, the manchette pipes are installed into the boreholes and secured into place by filling the annulus around them with a weak 'sleeve grout' made with a stable cement-based suspension.

In this process, much importance was given to the precision of the drilling, as the allowed borehole deviation was set to 3% at full length. The deviation of each single drilling is measured using a chain inclinometer. The drilling parameters are registered using a Jean Lutz LT3 system. These data, combined with the ►

records of the grouting parameters, give the engineers a detailed graphical representation of the work.

GROUTING

Grouting starts when the sleeve grout has reached a minimum strength of 200kN/m², no earlier than 2-3 days after the installation of the TAM pipes. The grouting sequence, according to the project requirements, includes primary and secondary injections. The primary injection is carried out with a stable cement-based suspension (ready mix with low chromate content binder) on the entire treated area. The secondary grouting is made with a high-penetration soft gel (low-viscosity aqueous solution of sodium silicate and sodium aluminate) on only the outer edge of the section.

Overview of the job site with Comacchio drill rig MC 1200 and grouting equipment

An automatically controlled mixing plant ensures the preparation of the different grouts. The injection is carried out using double-packers from a fully computer-controlled injection plant with 10 piston pumps. The pumping rate is adjusted inside the plant during the grouting process, in order to obtain a progressive increase of pressure and consequently, saturation of the pores.

The most significant injection data (flow rate, volume and pressure) are recorded continuously for each of the approx. 250,000 grouting processes and allow a detailed monitoring of the injection work.

Investigation tests with coring techniques are foreseen to control the quality and homogeneity of the injected soil. Moreover, Lefranc tests are carried out to check the permeability of the treated ground over the whole tunnel length.

The core drillings showed a fairly good stiffness and homogeneity of the treated soil, thus demonstrating a good penetration of the grouting products. The results of the first Lefranc test are comprised between 5 and 7×10^{-7}m/sec, thus showing a good success of the injection process also in terms of residual permeability to water.

The excavation work for the tunnel under Karl-Friedrich-Strasse is scheduled to be completed in the summer of 2016.