SHIELD-DRIVEN TUNNELS WITH OR WITHOUT COMPRESSED AIR

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STATE OF THE ART

Operating under compressed air is an essential method for construction of subaqueous tunnels and those passing through silt. Tunnels penetrating water-bearing sand or gravel may also require compressed air, unless the water table can be lowered by drainage. In the Chicago and Detroit areas, compressed air is used to support the ground in impervious clay and, sometimes, to prevent the entrance of explosive gases.

The following discussion of major shield-driven tunnels describes the state of the art, the problems, and the imposed restraints. No one method is considered to be best, for the method used will depend on specific project conditions, which vary widely.

The initial Chicago subway system was built in the period from 1938 to 1943 and was 12.4 km (7.7 miles) in length. The single track horseshoe tunnels, about 7 by 7 m (23 by 23 ft) in cross section, passed through a soft impervious blue clay. All were hand mined, except for that section under State Street where a shield was employed. Compressed air was specified, and most contractors carried 82.7 to 103.4 kPa (12 to 15 lb/in^2). Little water was encountered in this ground and little, if any, explosive gases.

The Chicago tunnels were 13.1 m (43 ft) below the surface, which gave about 6 m (20 ft) of cover. Since this ground weighed 1762 kg/m^3 (110 lb/ft^3), the weight on the roof was about 105 kPa (2200 lb/ft^2). Thus, an air pressure of 103.4 kPa (15 lb/in^2) was equivalent to the weight of the ground. Liner plates and steel ribs were specified. Most contractors concreted every other day so that the ribs and plates only supported the ground for 24 h. Since the pressure was less than 103.4 kPa (15 lb/in^2), medical locks were not specified or installed and, as far as can be ascertained today, there was not a single case of the bends.

There are nine vehicular tunnels under the Hudson and East Rivers in New York, all shield-driven with compressed air. The primary lining consisted of cast iron segments 9.4 m (31 ft) OD, with a shove of 7620 or 8128 mm (30 or 32 in). These tunnels had a secondary lining of concrete with tile finish.

There are about 30 additional railroad and rapid transit tunnels under the same rivers. The outside diameter varies from 5.1 m (16 ft 7 in) to 7 m (23 ft). The rapid transit tunnels are 5.5 m (18 ft) OD. These all have a primary lining of cast iron of the "heavy" type with a web thickness of 35 mm (1$^3/_8$ in) and no secondary lining. The shove in all cases was 7620 mm (30 in). Air pressure averaged about 158.6 kPa (23 lb/in^2) with a maximum of 275.8 kPa (40 lb/in^2).

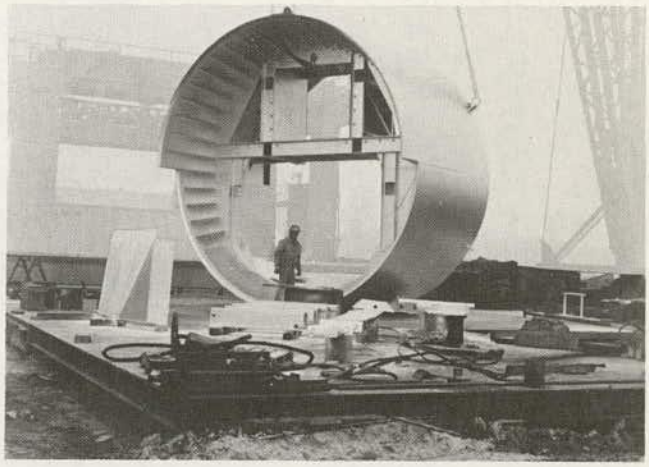
The Bay Area Rapid Transit (BART) system in San Francisco is 120.7 km (75 miles) long with 30.6 km (19 miles) in subway. This includes 5.8 km (3.6 miles) of the Trans-Bay section, which was built by sunken tube methods. Fabricated steel plates furnished by the owner were used in the 12.9 km (8 miles) that were shield-driven. These segments were 5.3 m (17½ ft) OD with 1524-mm (6-in) ribs and designed for a 7620-mm (30-in) shove. These plates were sprayed in the shop with a coal tar epoxy. Later a cathodic protection system was installed to prevent erosion of the plates by stray electrical currents.

On the Oakland section of BART, specifications required that the contractor install a complete compressed air system before beginning work. This included steel bulkheads, man and muck locks, and the compressor plant. All these tunnels, however, were eventually built in free air. In San Francisco, the specifications also required the installation of compressed air equipment. The section under the lower end of Market Street to the Ferry Building was driven under an average pressure of 103.4 kPa (15 lb/in^2), except that, when the connection was made to the Trans-Bay Tube, the air pressure was raised to hydrostatic pressure of 241.3 kPa (35 lb/in^2). One other shield-driven tunnel on the San Francisco side required compressed air for a short distance.

The rapid transit system for the Washington, D.C., metropolitan area will be 157.7 km (98 miles) long, of which 75.6 km (47 miles) will be in tunnel. Work began in 1969, and trains started running on a portion of the system in 1976. All the soft-ground tunnels are being shield-driven. Most of the contractors are using rib-and-wood lagging with an outer diameter of 6.1 m (20 ft). These have 1524-mm (6-in) wide flange beams at 1.2-m (4-ft) centers and 1524-mm (6-in) wood lagging. The lagging is being expanded as soon as it leaves the tail of the shield to eliminate or reduce settlement due to the tail void. There will be a secondary lining of concrete to give a 5-m (16½-ft) inside diameter as required for trains to pass.

Other contractors are using a fabricated steel segmented lining identical to those used in BART. One contractor is installing segments of ductile cast iron to give a 12 192-mm (48-in) shove. These primary linings of fabricated steel and cast iron do not require a secondary lining.

Tunnel shield.



FUTURE RESEARCH

Safety Regulations

The regulations of the Occupational Safety and Health Administration for tunnel construction by means of compressed air are strict. As a result, many tunnels that should be driven under compressed air are bulled through by crude and dangerous methods. This should be given further study and then discussed with OSHA with the possibility of modifying the regulations for work performed in "mild" air [less than 101.4 kPa (14.7 lb/in^2)].

Tail Void

The tail void is now first filled with pea gravel and then by low pressure grout. Methods are needed for filling the tail void more quickly and more effectively. Perhaps a foam or expandable slurry might be discovered.

Tail Seals

Many shields have been equipped with rubber tail seals to prevent grout, pea gravel, or water from running back into the shield. This has not been too successful because the seal becomes "frozen" into the grout, is torn off, and is nearly impossible to replace. An improved seal is needed.

Precast Concrete Segments

Precast concrete segments have been widely used in Europe, Japan, and Mexico, but have not been so widely used in this country. A precast concrete primary lining should be developed that would be reasonably watertight and would require no secondary lining.

Extruded Concrete Lining

In a tunnel project constructed several years ago in Buenos Aires, a shield was jacked against the still-liquid concrete that effectively filled the tail void. This scheme worked successfully and should be studied. No secondary lining was required.

Backhoes

Many shields, designed for hand mining, are equipped with a backhoe to break down the face and pull the muck back onto the loading conveyor. A more efficient backhoe is needed to improve the rate of progress in shield-mined tunnels.

Smaller Subway Cars

Rail rapid transit systems in San Francisco and Washington, D.C., use a subway car that is 3.2 m (10½ ft) wide and requires a tunnel with an inner diameter of 5 m (16½ ft). Cars in Chicago are 2.8 m (9⅓ ft) wide, and cars in Montreal are 2.6 m (8½ ft). Small U.S. cities cannot anticipate crowds as large as those in big cities and should, therefore, consider using narrower cars. Since the cost of the shield-driven tunnel varies with the square of the diameter, a smaller car could mean substantial savings. Car builders should be encouraged to prepare designs for such a car.