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El Azhar road tunnel—Cairo's new frontier

The historic Islamic centre of Cairo is now a more pleasant place to be thanks to a new, state-of-the-art road tunnel through the middle of one of the world's largest cities. The new 2·4 km long, twin-bore El Azhar road tunnel was designed and built in just 40 months to Europe's highest fire-safety standard. It has pioneered the use of a reinforced fire lining, which protects the tunnel structure from temperatures in excess of 200°C and thus prevents spalling. It also has an unusual escape system—rather than escaping through cross-passages between bores, users slide down into a safe passage beneath each road deck. This paper describes the design and construction of this innovative, fast-track project.

Cairo is now one of the world's largest cities, with a population estimated at 18 million and with over 1 million vehicles. One of the city's most urgent and newly acknowledged tasks is to reverse growth-related environmental degradation and, in this regard, the development of underground infrastructure is seen as its new frontier.

Egypt's National Authority for Tunnels, a state entity that had acted as project owner for the development of the Cairo Metro since the early 1980s, expressed an interest in building an urban road tunnel below the city centre. The tunnel would have the multiple purposes of

- decongesting vehicular traffic in the immediate city centre (Fig. 1)
- preserving Islamic Cairo from further urban degradation
- providing faster cross-city access for cars and buses (lorry access being excluded)
- permitting the removal of flyovers built in the city centre in the 1970s and thus creating a more pedestrian-friendly area
- reducing traffic pollution and noise locally


Fig. 1. Congestion in central Cairo—the new tunnel is taking 50 000 vehicle movements a day below the surface

By capitalising on its experience of having constructed lines 1 and 2 of the Metro, Vinci Construction Grands Projets (then Campenon Bernard SGE) put together a joint venture of contractors (Arab Contractors O. A. O & Co., Bouygues, Eiffage, Intetectra BTP, Soletanche Bachy France and Spie Batignolles BTP) to design and construct a twin-bore road tunnel running from Opera Square to Salem Saleh Street, the main urban highway leading to the airport. A contract with the National Authority for Tunnels was let in mid-1998.

Developing a feasible design

The buildings of historical and religious interest in central Cairo are spread in an extremely dense and poorly built urban housing matrix, which is overpopulated and often on the verge of collapse.

The conceptual brief for the tunnel contract used the first principles of urban tunnelling, by proposing an alignment below the most prominent road arteries at the surface in order to reduce surface settlements from ground loss during tunnelling. One bore followed El Mosky Street and the other was under El Azhar Street (Fig. 2).

The transformation of the conceptual scheme into a firm feasible design then became an optimisation exercise in

- avoiding underground constructions
- minimising land-take at the surface
- minimising the diversion of public utilities
- minimising the potential for the settlement of buildings
- minimising traffic disruption
- maintaining safety criteria
- choosing land at the surface that was suitable for the authorities and third parties.

Shoehorning the project into what is one of the most densely populated parts of the planet was a challenge to the creativity and resourcefulness of an extensive team of design engineers. Owing to the lack of appropriate data in the project area, traffic studies and topographical and existing building surveys had to be conducted along the proposed alignment in order to establish a workable design baseline. Many options had to be examined, evaluated and returned to the drawing board for revision.

Moving the route to avoid piles

As data impacting the project came to light, it quickly became apparent that the flyovers that were to be demolished once the tunnel was in service were founded on piles. This caused the tunnel alignment to be re-examined and, similarly, the subsequent discovery of the depth of piled foundations for the recently built El Azhar university and hospital, and recently built sewers, drove the central section of the tunnel alignments away from the conceptual design routing below the main roads.

Although the extremities of the project could be maintained as designed, the central parts of the tunnel alignments were pushed closer together and below buildings in the Bazaar area (Fig. 3). The central ventilation stations thus became units serving both of the tunnels rather than each one individually and required larger but fewer land-plots at the surface.

Options were considered whereby a central mega-ventilation plant would service the project, but this was discarded on account of the unacceptable time and cost for expropriation of a large land-take at the surface. Escape routes from one tunnel to another were ensured by cross passages and the ventilation stations, which could then provide egress to the surface. The geometric and performance criteria that were finally settled on for the tunnel were as set out in Table 1.

Sewer pushes tunnel deeper

Saleh Salem Street and Attaba Square are, respectively, 50 m and 19 m above sea level. The tunnels were now passing below more buildings and the more fragile

Table 1. Tunnel geometry and performance data

Tunnel facility	Extent/capacity
Overall tunnel length	2320 m
Attaba cut-and-cover section length	200 m
Bored tunnel length	1700 m
Salah Salem cut-and-cover section length	350 m
External tunnel diameter	9·15 m
Internal tunnel diameter	8·35 m
Lane width	6 m
Permissible vehicle height	4 m
Walkway width	0·738 m and 1·073 m
Maximum permitted speed in tunnel	50 km/h
Minimum radius at ramp entrance/exit	100 m

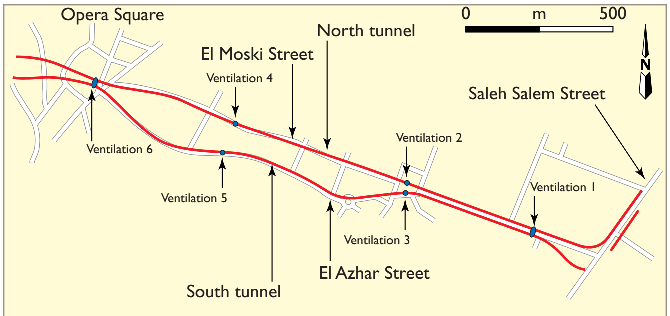

Fig. 2. Concept route for tunnel with north and south bores following main roads

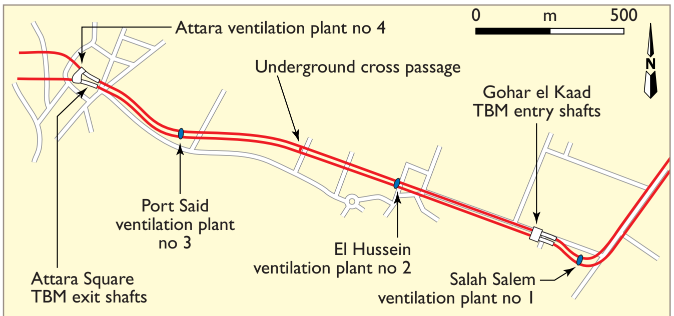

Fig. 3. Final design route for tunnel avoided old flyover piles and resulted in fewer, larger ventilation stations

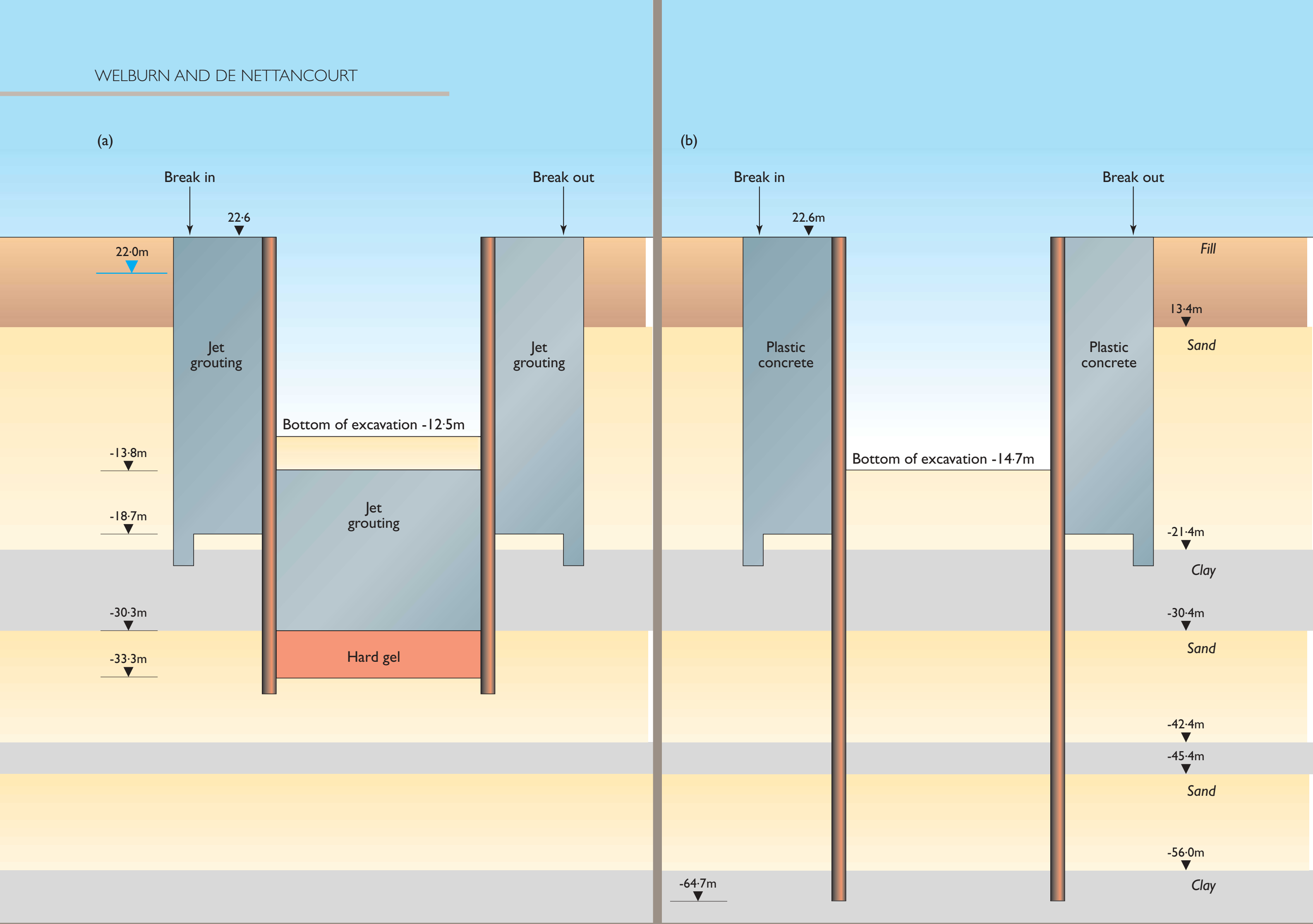

Fig. 4. Original plan for resisting groundwater uplift on ventilation stations involved installing a jet-grouted gel plug between the diaphragm wall (a); whereas the contractor opted to extend the walls down to a watertight clay layer up to 87 m below the surface (b)

structures had to be temporarily supported, with sensitive foundations protected by specific soil treatment, such as jet grouting and fine cement permeation grouting.

Fitting the road tunnel into the city subspaces was also conditional upon satisfactorily passing a 5 m diameter main collector sewer, which was near Port Said Street ventilation station and located 17 m below ground. Putting the sewer out of service—whether for protective bracing, diversion or post-passage repairs—was simply not an option for consideration. Consequently, the tunnel had to be designed to pass 4 m below the sewer in order to limit tunnel-induced settlements to 10 mm. However, this caused the longitudinal profile of the tunnel to be lowered, increasing the tunnel gradient and the depth of the Port Said ventilation station to 37 m.

The design construction method used for the Cairo Metro stations, where rafts were at approximately 25 m depth, was initially to be used for the El Azhar ventilation stations. This would have required constructing diaphragm walls to approximately 60 m depth and grouting a hard gel plug to ensure watertightness. Jet grouting from the raft to the plug would have acted in friction against the diaphragm walls to counter the upward thrust of hydrostatic pressure (Fig. 4(a)).

Diaphragm walls 87 m deep

The El Azhar ventilation stations were deeper than the Cairo Metro stations, particularly so at the low point at the Port Said ventilation station. Further ground investigations during the mobilisation phase showed that deep layers of clay prevailed, which could form a naturally impermeable horizon.

A different optimised design and construction method was quickly chosen for the ventilation stations. This dispensed with the grouted plug and involved constructing diaphragm walls through to the watertight clay layers (Fig. 4(b)). To do this, 1·5 m thick diaphragm walls were sunk to 87 m in depth at Port Said, which was believed to be a new record in an urban environment.

The biggest challenges in constructing accurately at such a depth from the surface (ensuring verticality and continuity) were overcome by fitting and controlling the KS3000 and Hydrofraise 4000 and 8000 rigs with computer-guided gyroscopes. However, other important challenges to deep foundation construction were

- avoiding structural damage to, and settlements of, surrounding buildings
- avoiding damage to public utilities
- working with limited headroom around and below the flyovers at Attaba
- working with the three diaphragm wall rigs, two cranes for handling, two 450 m^3 de-sanding plants and a Puntel drilling rig in a confined 2000 m^2 site at Port Said.

Tunnel boring machines define traffic gauge

The fast-track project was based on using one of the 9·35 m diameter Herrenknecht Hydroshield tunnel boring machines that had been used for the construction of the Cairo Metro and that was still mobilised in Cairo with its operational resources. This choice had a direct impact on the traffic gauge, which was limited to a height of 4·0 m and to two

3·0 m wide lanes (Fig. 5).

The final longitudinal profile (Fig. 6) gave gradients in the tunnel of 5·1% (maximum locally) from the western portal to Attaba and thereafter 2% to Port Said, which marked the lowest point of the tunnel. The gradient to El Hussein was set at 1·33%, and finally sloping out at 4% to the eastern portal.

Although a wealth of knowledge of sub-soil conditions had already become available during the excavation of the Cairo Metro, around 30 boreholes were sunk along the alignment, with several serving as piezometers. These showed, at the tunnel alignment, Quaternary deposits of fluviatile origin deposited in a sinuous river.

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Flints and bacteria encountered underground

The river deposits had been made during two distinct phases during the middle and late Pleistocene periods. The first phase is represented by cross-bedded, coarse sand facies, as well as the bedded sands. These latter sands are thought to have been deposited in the flood stage, probably in the plane-bed phase of the upper flow regime. The second phase is represented by the finer sand facies, as well as silt and clay. Horizontal silt and clay beds were deposited during the falling stage of the flood.

The tunnel boring machine, using break-out/break-in ground treatment at the entrance and exit of each station (Fig. 7),

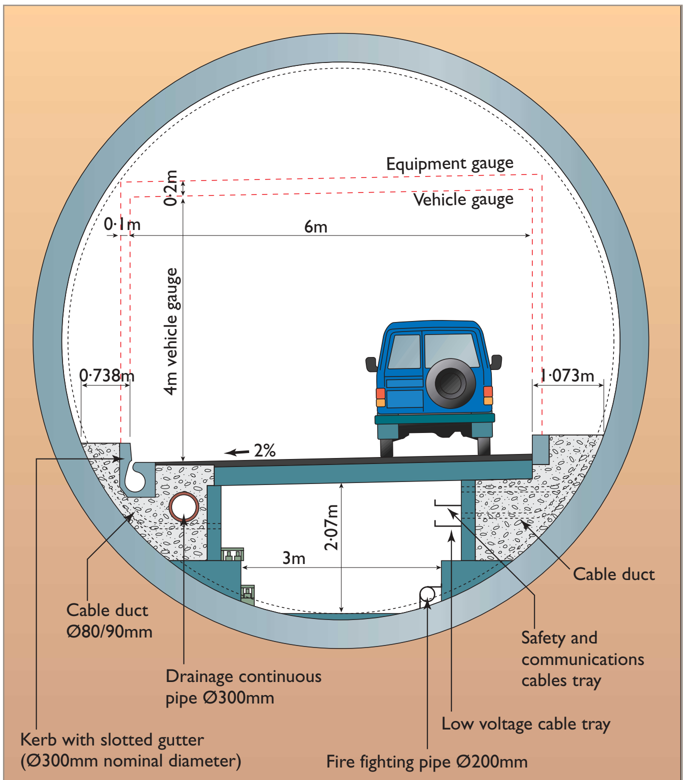

Fig. 5. Design cross-section of tunnel showing traffic gauge

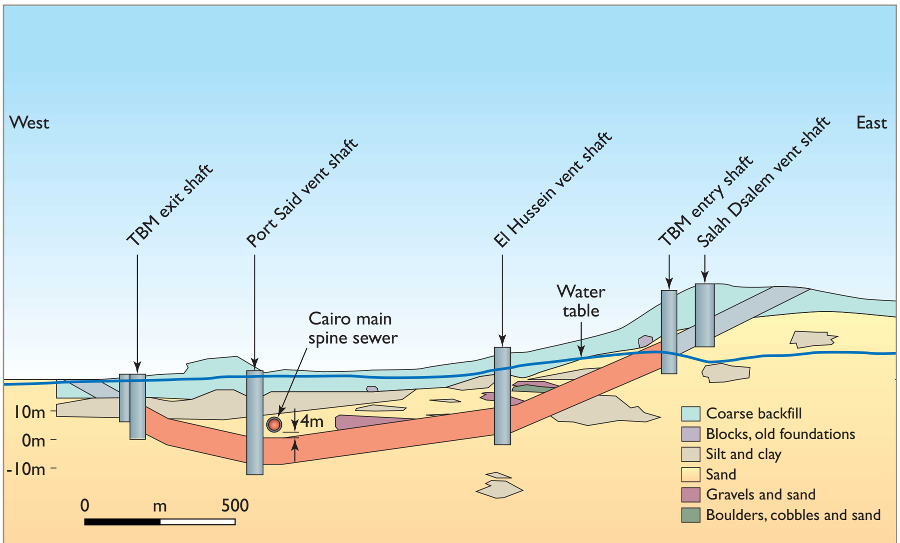

Fig. 6. Longitudinal profile was governed by need to pass at least 4 m below an existing main sewer

Fig. 7. The 9·35 m diameter Herrenknecht Hydroshield tunnel boring machine entering the El Hussein ventilation station through grouted ground

had proved its worth in constructing the Cairo Metro and the diaphragm walling was also a tried-and-tested success. The only real problem encountered during the drives was a localised pocket of flint that had been grouted in the break-out leading into Port Said ventilation station. This caused some delay and unexpected wear on cutting tools during the tunnel boring machine drive.

No contaminated soil was encountered during the excavations, but anaerobic bacteria, which die upon contact with the air, were prevalent. These bacteria present no risk to construction personnel but feed on hardener reagents, which, in turn, cause gel cohesion to diminish. Accordingly, mineral gels or cement were used in the deep foundation works.

Keeping the air fresh

The tunnel ventilation design involved careful evaluation of air quality, air pollution and fire-life safety seeking to

- prevent the dangerous accumulation of vehicle-emitted pollutants, such as carbon monoxide (CO)
- help maintain visibility within the tunnel by preventing the accumulation of those pollutants
- control the movement of smoke and hot gases during a tunnel fire
- be maintenance friendly so that access to fans, dampers and associated components does not require closure of a tunnel.

The recommendations and publications of the Permanent International Association of Road Congresses (PIARC) provided guidelines for system design. Data gathered for Egypt's environmental legislation, together with the traffic authority's surveys and traffic counts, were reviewed to determine the fresh air needs in the road tunnels. Traffic assumptions were determined as shown in Table 2.

Different ventilation concepts were considered but, finally, after considering traffic densities, the tunnel profile, gauge and clearance, and the desire to minimise facilities at the surface, a longitudinal ventilation system with intermediary Saccardo nozzles and jet fans at the tunnel extremities was decided upon. The Saccardo nozzle system operates on the principle that a high-velocity air-jet, injected longitudinally into the tunnel, can induce a high volume air flow in the tunnel, as well as renewing a major part of the air in the tunnel. Its advantages are

- suitability for reduced tunnel gauges
- reduced number of moving parts to maintain
- maintenance can be accomplished without impeding traffic flow
- noise level in the tunnel is decreased
- high fan efficiency.

Fan speeds drop in fire situations

Several fire scenarios have been considered at various points throughout the tunnel leading to different ventilation settings. In addition, an innovative strategy has been developed consisting of the following two distinct phases.

The first phase seeks to reduce air velocity to approximately 1 m/s in order to reduce the spread of smoke and thus protect tunnel users during an evacuation. This phase is based on predefined settings of the ventilation system and on an algorithm that modifies these settings according to real-time measurements in the tunnel.

The second phase aims at giving the emergency services a smoke-free route to the fire and protecting the tunnel structure by achieving a higher air velocity (3–4 m/s) that reduces the maximum air temperature along the tunnel.

Alps tunnel fires lead to design rethink

The tunnel was equipped with a wet-riser fire-fighting system served by a 200 mm diameter supply with hydrants located at approximately 100 m centres. However, fire protection design for the project was developed against the backdrop of a series of road tunnel fires in the Alps (St Gotthard road tunnel on 31 October 1997; Glenalm Tunnel on 8 September 1998; Mont Blanc road tunnel on 24 March 1999) and led to a re-evaluation of safeguards for tunnel users, the tunnel itself and its equipment.

The Alpine tunnel accidents sadly confirmed that prevalent safety concepts were no longer compatible with traffic flows that had increased over the last decades. It was clear that bi-directional road tunnels presented a risk to tunnel users and that 400 m spaced emergency exits could not guarantee their safety.

Although heat is the biggest threat to the tunnel and its equipment, experience has proven that toxic gases and particles in undiluted smoke are more life threatening than heat. Thus, people have a greater chance of escaping harm when the lower portions of the traffic space are free of smoke, and provide enough air and visibility to enable people to evacuate the tunnel.

Avoiding the spalling effect

The events in the Alps caused tunnel designers to refocus on standards for the El Azhar tunnel. What they came up with was a protective fire-coating for the tunnel and an ingenious emergency escape chute scheme.

Although the tunnel does not allow the transit of lorries, let alone petrol tanker trucks, the engineering team decided to protect the tunnel against the heat generated by a 100 MW fire. In preserving the tunnel, it was necessary to safeguard against the 'spalling effect', whereby when concrete is subjected to elevated temperatures, any water contained inside expands as it evaporates and disintegrates the concrete in exiting the structure. This recurring process, which progressively destroys the entire concrete body, starts at approximately 250°C.

Table 2. Estimated vehicular traffic

No. of vehicles over 6 h	Attaba eastwards towards Salah Salem	Salah Salem westwards towards Attaba
Saloon cars	18 000	24 000
Buses	1000	1400

Considering that the water table is located just below the ground surface, spalling damage of the segments (Fig. 8) would have catastrophic consequences. Such a phenomenon could, within minutes, lead to the loss of the structure and cause huge surface settlements, which would, in turn, inevitably lead to building collapses and casualties. In this context, protection of the segments from heat was of prime importance and it was thus decided to protect the concrete surface from temperatures in excess of 200°C.

Choosing a suitable fire lining

As the standards and requirements for protective coatings vary from country to country, it was decided that testing would be performed in accordance with the most rigorous standards, namely those established by the Dutch Tunnel Authorities (RijksWaterStaat).

The heat-testing curve defined by the RijksWaterStaat is currently the most stringent in Europe and requires test samples to be exposed to 1350°C during a minimum period of two hours. It is noteworthy that the heat-testing curve is not directly related to the magnitude of the fire designed for (100 MW in this case). Indeed, 100 MW corresponds to an amount of burning material, whereas the resulting temperature is affected by ventilation, the volume of the tunnel and other external parameters.

The chosen fire-protective coating was selected from eight other products available on the market. The choice was made on the basis of the following main considerations.

- *Fire resistance according to RijksWaterStaat standards*—it was important to select a product that minimised the material thickness to the extent consistent with protecting the segments from temperatures in excess of 200°C.
- *Structural resistance*—resistance to compression obviously has a direct impact on the product life-span. Furthermore, coatings with higher strength would facilitate the fixing of light equipment and accessories. Products with higher compressive strength were thus favoured.
- *Washing*—for obvious maintenance reasons, the client required that the coating should withstand heavy-duty washing. Accordingly, samples of those products most likely to be selected were subjected to intensive high-pressure water jet streams (in the range of 50 bars) to simulate the long-term effect of cyclic washing processes and to evaluate the impact on the product.
- *Ease of application*—trial applications for several products were carried out on real concrete segments and were assessed to evaluate the ease, the time and the cost of application.
- *Manufacturing rates and quality*—special care was taken to assess manufacturing facilities in order to evaluate each of the suppliers' capacities in terms of production rates and quality.

After comparing all products available on the market on the basis of the above key criteria, Firebarrier 135, produced by Thermal Ceramics, was judged to be the optimum product.

Mesh prevents lining collapse in fire tests

It was decided not to rely solely on the lining bonding directly onto the concrete segments due to the extreme smoothness of the latter. Plastic-coated wire mesh was fixed to the segments at the mid-thickness of the lining with stainless steel bolts (Fig. 9). Bolt diameters were selected to be able to support cable trays and light equipment, such as cameras, in addition to the mesh. Connectors were homogeneously placed at 450 mm centres and special traction tests were carried out to

Fig. 8. Tunnel segments are under up to 30 m of groundwater, so it was critical to protect them from spalling damage during a fire

Fig. 9. A 47 mm thick Firebarrier 135 lining being sprayed onto plastic-coated wire mesh fixed to the tunnel segments—in a 1350°C fire this keeps the temperature of the segments under 200°C for at least two hours

Fig. 10. Completed lining has colour variations and suffers from micro cracking, but this does not affect fire properties

check the efficiency of the mesh and its connectors.

The nominal coating thickness was estimated at 47 mm by theoretical calculations supported by electronic simulations, and then confirmed by fire tests carried out to RijksWaterStaat requirements in the SINTEF Fire Department in Norway. The nominal coating thickness was sprayed on to concrete plates, which were made out of the same concrete mix, and which were of the same thickness and reinforcement as in the El Azhar tunnels. The concrete plates were placed on top of a box-type oven and the required testing temperature was induced from below.

The installation was equipped with several thermocouples to survey the temperature within the coating and at the concrete interface. The various test results all showed that the temperature at the interface between the concrete and the coating never even reached the 200°C limit. In addition, the wire mesh and connectors prevented coating collapse during the trials. These tests confirmed that the product choice, its calculated thickness and the wire mesh with its fixing devices were more than appropriate to protect the concrete lining from extremely high temperatures.

Colour variations and shrinkage cracks

The application of the lining in a tunnel was a world first and there was very little information available. For future reference, it is therefore worth recording the following points concerning colour homogeneity and shrinkage cracks.

Being a cement-based product, the colour of the applied coating was not perfectly homogeneous (Fig. 10). The final coating presented tone variations similar to those offered by fair-faced concrete surfaces. In order to obtain a perfectly final homogeneous surface colour, the raw material components should not only be chosen according to their physical properties but also according to their colour tones. Such an additional quality parameter obviously has a cost incidence, which needs to be considered when planning a road tunnel.

Owing to differential shrinkage phenomena and to the relatively low E-modulus, evenly distributed shrinkage micro cracks (below 0·2 mm) appeared on the lining surface. It has been proven that such cracks are harmless and do not affect fire-resistant properties or the structural strength of the product.

Escape chutes provided at 100 m centres

The original El Azhar road tunnel design satisfied the most stringent European safety codes and provided emergency exits at 400 m centres. These led into cross-passages, allowing users to escape from one bore to the other. After construction had already started, some European countries started to revise their tunnel safety regulations so the exit spacing had to be redesigned to 200 m centres. Cross-passage construction at a depth of 30 m below the water table in Cairo's congested environment

Escaping users enter by short slides and then walk to the ventilation stations from where there are stairs to the surface

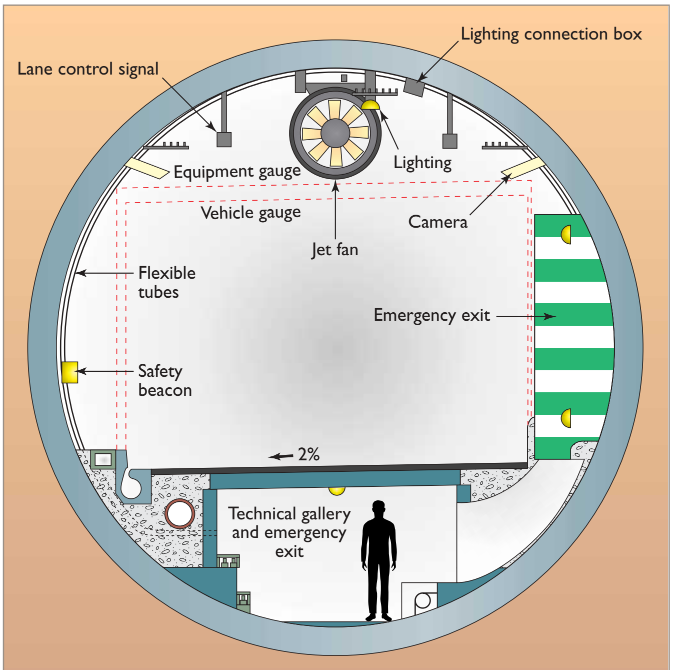

Fig. 11. Cross-section of tunnel bores at emergency exit, showing escape chute down to technical gallery beneath road slab

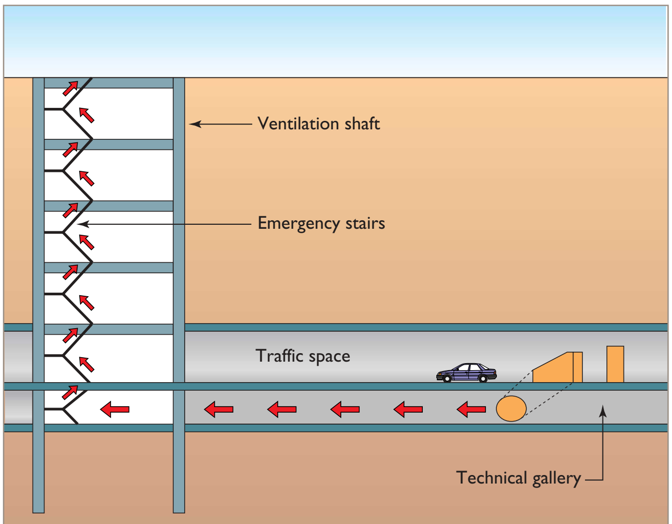

Fig. 12. Escape route to surface by way of chutes, technical gallery and ventilation shafts—maximum distance to a shaft is 400 m

is a difficult operation and with the potential for significant construction risks.

The contractor therefore proposed that the 3 m wide technical gallery, with a 2·07 m headroom and located below the road slab, be transformed into an escape corridor. Escaping users enter by short slides (Fig. 11) and then walk to the ventilation stations from where there are stairs to the surface (Fig. 12). Slides had previously been used for such purposes in the 9·5 km long Tokyo Bay Aqualine road tunnel completed in 1997.

The slide scheme represented a considerable safety enhancement for the project, since emergency escape points from the tunnel were set at 100 m intervals as opposed to 400 m and 200 m centres previously envisaged. It did require, however, that the gallery be lightly pressurised to prevent smoke from entering and be well lit at all times. The chute entrances were equipped with warning lights at the carriageway level (Fig. 13) and lighting in the chutes themselves

Fig. 13. Highly visible emergency exits are positioned every 100 m along each tunnel bore

Table 3. Tunnel mechanical and electrical data sheet

Tunnel facility	Extent/capacity
Overall tunnel length	2320 m
Bored tunnel length	1770 m
Ventilation	
• Saccardo stations	24 motor fans (2 m diameter, 220 kW each); Saccardo ventilation stations at Port Said and El Hussein
• jet fans	12 per tunnel—jet fans designed to operate at 400°C (1 h)
• extraction stations	4 motor fans (2 m diameter, 75 kW each), extract stations at Attaba and Saleh Salem
• auxilliary ventilation	22 fans for staircase and cross-passage ventilation; 6 fans for emergency egress ventilation
Control centre	At Salah Salem, fully redundant supervisory control and data acquistion system—24 h video supervision, 4 monitors covering entrance and exit, 4 monitors for circular scan sweep, 2 monitors for alarms from emergency post
Emergency call stations	41—each with 2 fire extinguishers, 6 kg polyvalent powder equipped with surveillance contact and 1 telephone handset
Emergency egress chutes	27
Cameras	34 fixed cameras for each bore; 4 movable for tunnel entrances and exits
Hydrants	48
Traffic flow detectors	Each bore has 6 inductive loops
Fire-fighting stations	1 at Attaba; 2 at Gohar—each station has 3 tanks of 60 m^3, 2 full and 1 empty available for the maintenance of others
Air monitoring	Each bore has 5 CO monitors, 5 smoke sensors and 4 anemometers
Power supply	Installated capacity of 6830 kVA, mains connections at Attaba and Salah Salem, 3 generators at Salah Salem
Radio operations	1 leaky feeder radio antenna

(Fig.14). Accordingly, extensive adaptations had to be carried out to the carriageway and technical gallery (Fig. 15) in the shortest of times in order to deliver the project on time.

The tunnel mechanical and electrical equipment is summarised in Table 3.

Designed and built in just 40 months

All project personnel contributed individually and collectively with enthusiasm and vigour to complete the project. The client's management team recognised that a reciprocal momentum was necessary to keep this fast-track project on an acceptable schedule and did everything within their power to contribute to the attainment of acceptable deadlines (Fig. 16).

The project was taken from an entry on the Government's infrastructure planning list to operational reality in less than four years. This constitutes an impressive achievement under any circumstances.

Design and construction performance

Fig. 14. Entrance to escape chute needs to be kept lit at all times

Fig. 15. Exit from escape chute in technical gallery beneath road deck—positive air pressure prevents smoke entering

Fig. 16. Construction of El Hussain ventilation station—round-the-clock working resulted in rapid progress

may be summarised by the following principal milestones.

- May 1998—contract signature.
- November 1998—basic design completed.
- Autumn 1998—tunnel boring machine reconditioned and lowered into start shaft at Gohar.
- January 1999—boring commenced for tunnel 1.
- October 1999—tunnel 1 complete.
- Autumn 1999—tunnel boring machine disassembled and returned to Gohar.
- January 2000—boring commenced for tunnel 2.
- May 2000—boring of tunnel 2 complete.
- October 2000—tunnels fitted out with precast concrete decking and walkways.
- Summer 2001—completion of equipping of tunnels and stations.
- October 2001—inauguration and opening to the public.

The works themselves involved the following quantities

- concrete poured—135 000 m^3 (diaphragm walls 80 000 m^3, structures 55 000 m^3)
- total drilling length for grouting—122 000 m
- grouting—20 000 m^3
- jet grouting—28 000 m^3
- reinforcing steel for structures—13 000 t
- peak number of personnel—2000.

An incremental improvement

The El Azhar road tunnel is a new route in the heart of Cairo. It is bringing some relief to the chronic and severe traffic congestion that has been, for some time, a characteristic of the city. Critics may say that, although the tunnel may provide rapid exit from the city to the Saleh Salem highway, in the opposite direction traffic coming into the city can only exit into near gridlock situations.

The response is that global solutions to contain Cairo's environmental degradation are simply not available. Relief can only come from successive and incremental improvements of the urban infrastructure, and the authorities are aware of this.

The El Azhar road tunnel is a modern, robust, state-of-the-art facility. Its operation will require rigour and thoroughness, qualities that have been successfully demonstrated in the management of other facilities, such as the Cairo Metro. Traffic engineers will need to adapt the surrounding roads and develop other congestion management strategies, but the El Azhar road tunnel is already relieving the historic centre of more than 50 000 vehicle movements a day (Fig. 17).

Acknowledgements

Contributions from Seitha (ventilation subcontractors), Soletanche Bachy France (deep foundations) and Jerome Furgé (Bouygues TP) are acknowledged with thanks.

Fig. 17. El Hussein ventilation station in new traffic-free area in central Cairo

References

1. Abinader, A. and Schmitt, P. *Les Travaux Speciaux du Chantier d'El Azhar ay Caire, Travaux, May 2000.*
2. Ramond, P. and Guillien, S. El Azhar road tunnels. *Proceedings of the Cairo Tunnelling Conference*, 1998.

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