

CHANNEL TUNNEL TUNNELS CONSTRUCTION

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Scope

Within the 5 years following contract award, 3 parallel tunnels, 50.5 km each, had to be driven and lined with high-strength precast segments : 38 km undersea, 3.2 underland in France, 9.3 km underland in UK. 2/3 of the total had to be excavated from UK side, and 1/3 from French side where ground conditions were unfavourable. 6 drives (total 12), 3 to the sea and 3 to the land have been conducted from each of the two tunneling sites, located as close as possible to the sea : Shakespeare Cliff (west of Dover) on the UK side, and Sangatte (west of Calais) in France.

The **service tunnel (ST)** has a internal diameter of 4.8 m (excavated diam.5.8 m).

The two **running tunnels (RT)** are at 30 m distance, lined diameter is 7.6 m (excavated diam.8.8 m). They are connected together by 194 piston relief ducts (every 250 m, diam 2 m), and by 270 cross passages (every 375 m) and 210 technical rooms (all diam 3.3 m) to the service tunnel, requiring special cast iron segments at each junction.

Geology and alignment

Many geotechnical investigations have been carried out across the Channel since 1875, including over 100 boreholes. Total information available including final investigation after contract award and geophysical survey undertaken in 1988, (specifically for crossing beneath the Fosse Dangeard and crossovers sites), comprised:

- 120 marine boreholes and about 1,000 km of geophysical (seismic reflection), traverse lines,
- adits and short length of tunnels excavated during previous attempts.

Optimum tunnelling conditions are within the Chalk Marl, clayey carbonate mudstone, weak (20 to 200 bars), homogeneous rock, believed to be mainly impermeable, with any water restricted to discontinuities such as faults or fissures concentrated on French side. It is a tunnelling medium adequate for TBMs.

High precision alignment

The tunnel alignment was a critical stage in the design process. It was later optimised using experience gained while driving the service tunnel itself, and design developments at the crossover and pumping stations, avoiding fault zones which would reduce tunnelling progress. Geometrical criterias applicable to a high-



Above : View of a running tunnel on French side at the beginning of the tunneling phase (1988), showing temporary fixed equipments (water pipes, ventilation duct diam 1600mm, power and radio communications cables, double track and walkways...). Below : Tunneling progress on 29th of April 1990, 7 months before first undersea breakthrough, showing forecasted ("M"), and final (black balls) meeting points.

speed railway impose large radius curves, leading to **drive 150 km of tunnels within 150 mm tolerances**: 40 mm for topography, 55 for TBM steering, 25 for segments manufacturing/erection (ring axis), 30 between surfaces of adjacent segments. TBMs, launched over 38 km distance, had to meet with precision !

Topographical survey

Different systems in UK and France

British maps are based on Mercator system, French maps on Lambert system. Sea level on both sides differed by 440 mm according to a 1958 study, reduced at 300±80 mm in 1987, measured at 360 mm after breakthrough.

Joint mapping and levelling

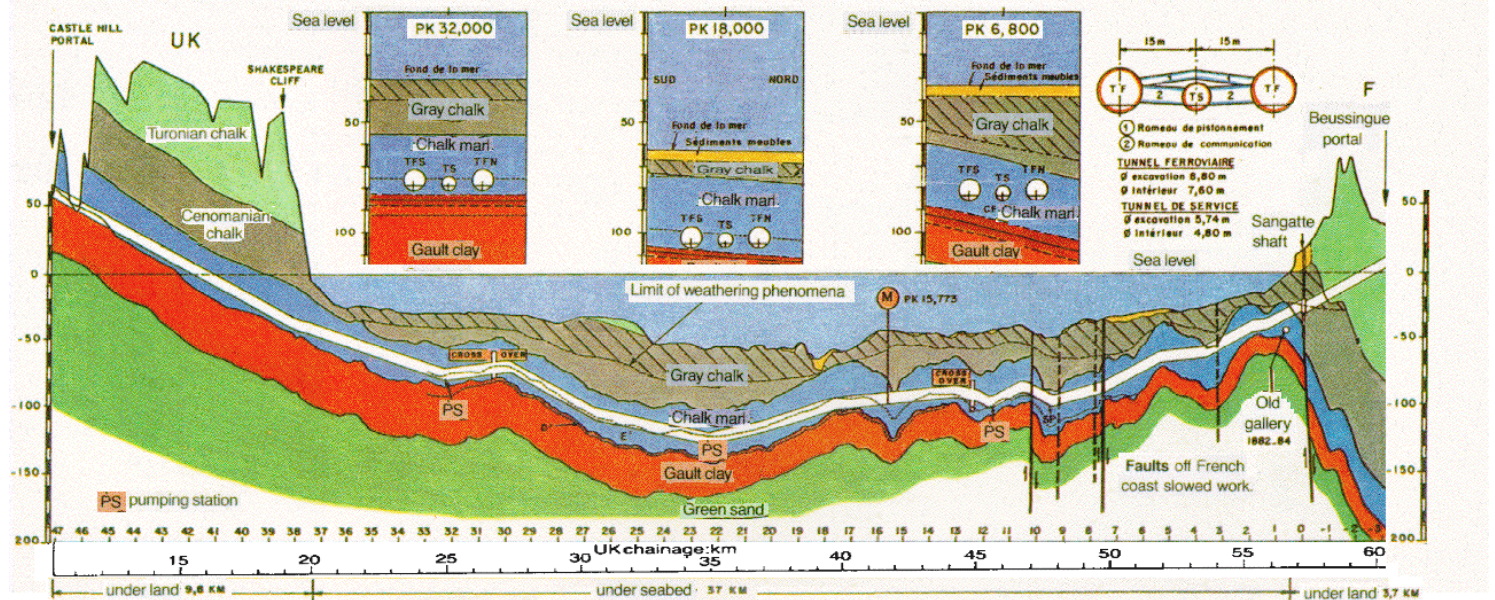
Mercator system was adopted, but based on the mid-Channel 1°30 East meridian. Satellite Global Positioning System (GPS, precision 5 cm for 50 km) was used and water movement studies reduced levelling uncertainty, leading to the RTM87 grid, and the NTM88 levelling ("Reseau" and "Niveau TransManche"). Final orientation



to the North required a gyrotheodolite with precise astronomical calibration and correction of all horizontal angles, locally different due to the Mercator system.

Survey brought underground

RTM87 was brought underground through the inclined adits of the UK side and the Sangatte shaft in France through benchmarks set at the tunnels starting points with a precision of 0.6 mm (5 mm error would have meant 1.5 m at 15 km distance). Grid was relayed along TBMs journey with computer correction of temperature, pressure, hygrometry. After first breakthrough, a reference point was at least available for running tunnels survey.



Geological profile and description of the works. Tunnel slope is between 0.2% and 1.1 %, often found at 0.6% on UK side and at 1.1% on French side.

Breakthrough actual precision

Once the marine service tunnel TBMs stopped at 100 m distance, measured lateral offset was 358 mm; levelling : 58 mm; chainage : 75 mm. Readjustment over the final 50 m, hand excavated, produced a smooth junctioning of the two drives.

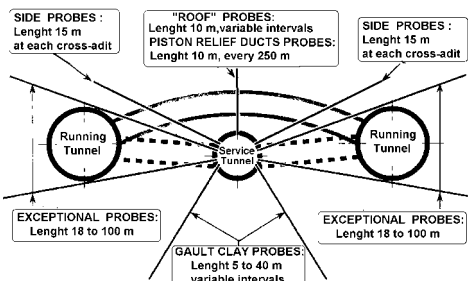
Running tunnels all came out within the 15 cm tolerance. Underland TBMs came out at less than 2 cm from the original alignment.

Tunnel Boring Machines

Design criteria on French side

Critical programme and unfavourable geology determined a whole tunnelling system (TBMs, back-up systems, linings, and overall logistics). Design criteria were:

- **progress without ground treatment in watery conditions in France**, especially the first 4 km undersea (where the chalk is fractured), and 3.2 km underland, (below water table).
- **progress at high speed** (4.4 lm/h) in dry, fair to good, ground conditions.
- **ensure safety and reliability for a highly complex, massive, tunnelling**



logistics designed for peak boring

rates. A huge, waterproof, shaft housed all French tunnels logistics at Sangatte.

TBMs description

11 TBMs were ordered by TML. On the UK side, 6 open, full-face TBMs (3 undersea and 3 underland) were used in conjunction with unbolted, expanded precast concrete linings by use of wedge-shaped key.

The 5 French TBMs have been launched from the Sangatte Shaft: 3 undersea, 2 underland, one being turned back to drive the north running tunnel underland. There are full face, earth-pressure type, and allow erection of watertight precast segments inside the shield concurrently with face excavation. Their unique design combines technologies for both soft ground underwater and hard rock.

The 3 undersea French TBMs include articulated double shield operating in closed mode in wet zones (minimum rate of 3 m/h), or in open mode at high speed in dry zones. Cutter chambers are sealed to withstand a hydrostatic pressure of 11 bars: excavated chalk had to pass through a two-stage pressure lock before being ejected at atmospheric pressure into the muck wagons. Containment is achieved at the end of the spoil extraction screw either through a dual discharge pump system or through a second screw creating a plug.

The 2 underland French TBMs included a single shield, Archimedes screw containment and a "casing rotator", to

withstand a hydrostatic pressure of 3 bars.

French TBMs guidance system

The ZED 260 guidance system used a laser beam, set up to a predetermined alignment, and received on a screen on the cutting head. After analysis, an on-board computer displayed, in the cab, differences between designed and actual **TBM's 3 dimensional position**, allowing the driver to correct by steering to zero. **Steering** was achieved by selection of the push rams housed in the telescopic section.

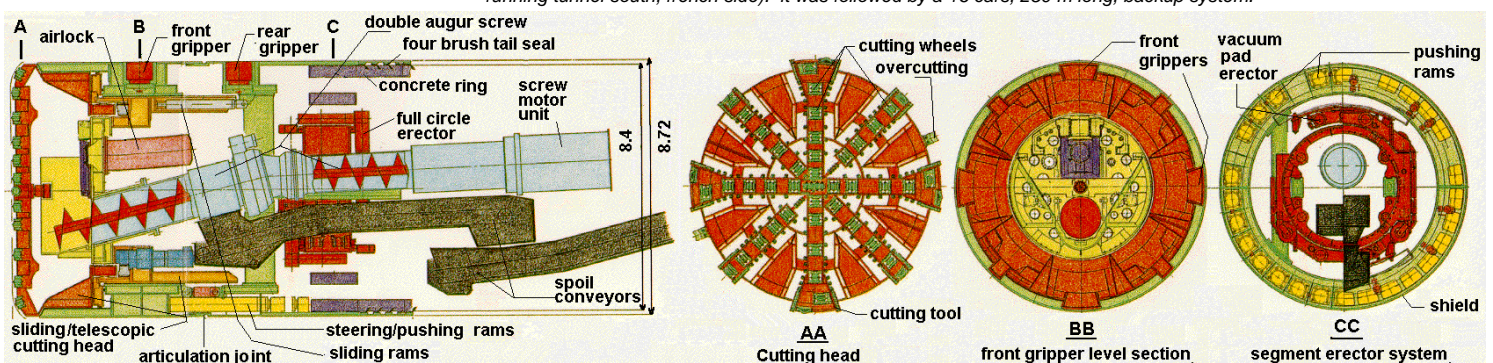
Real time monitoring in the cab of complete operational status of the TBM

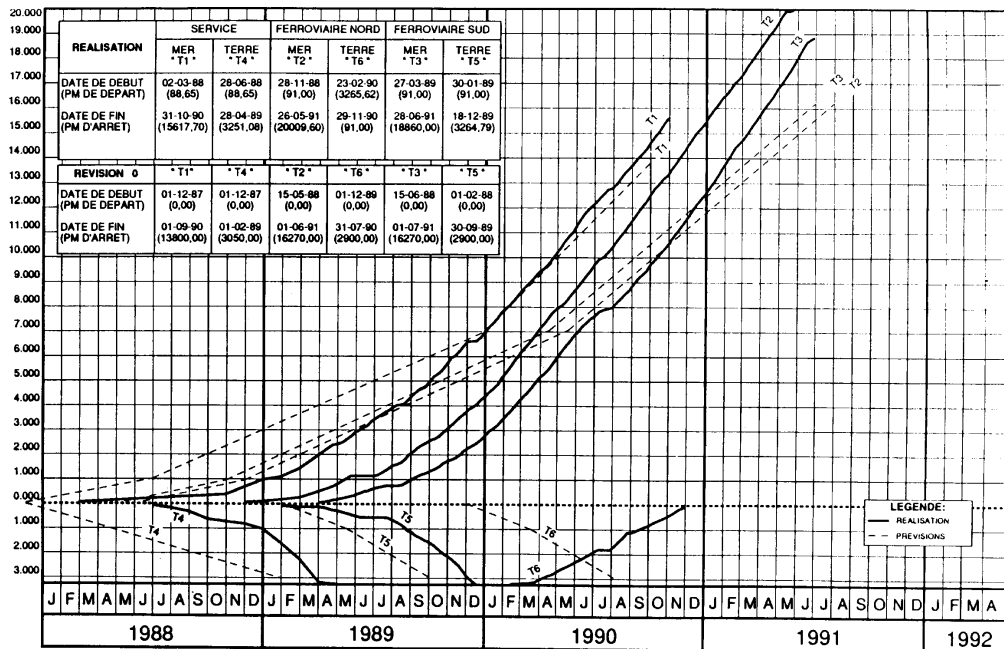
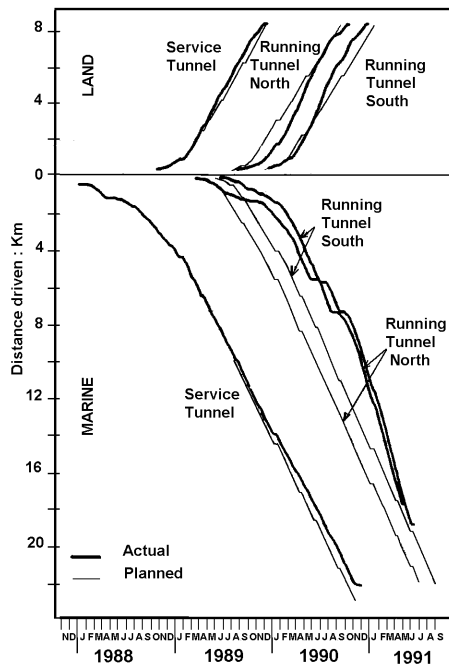
T3 process was ensured by an IBM 7532 supervisor: pressures, speed, stroke of hydraulic jacks, spoil rotating screws and tail seals, but also electrical intensity and instant power of the 12 motors, water injected flows - 20 bars and 30 bars - and earthpressure at 5 different locations of cutting chamber, plus rotating head position. Programmable controllers managed overall process safety and failure detection (ALSPA C350, 2000 I/O), grout injection (SIEMENS 115V), and segments feeder (TELEMECANIQUE TSX47-20). Main data were plotted and/or transmitted to surface. Long term tracing of segments rings main data was automatically available. Video screens showed conveyors operations.

Probes, ground treatment

Site investigation boreholes covered a grid of 1 km width only, leading to use the

Left : Probes on French side around the T1 (marine Service tunnel TBM). Below : Description of the TBM T3 (Marine running tunnel south, french side). it was followed by a 16 cars, 250 m long, backup system.





Above, top : Tunneling programme on UK side (left) and French side (right). Above image : Inside the control cab of TBM T3 (French marine south running tunnel). Right image : TBM T3 during preassembly at the factory. Bottom table, right : TBMs data on French side.

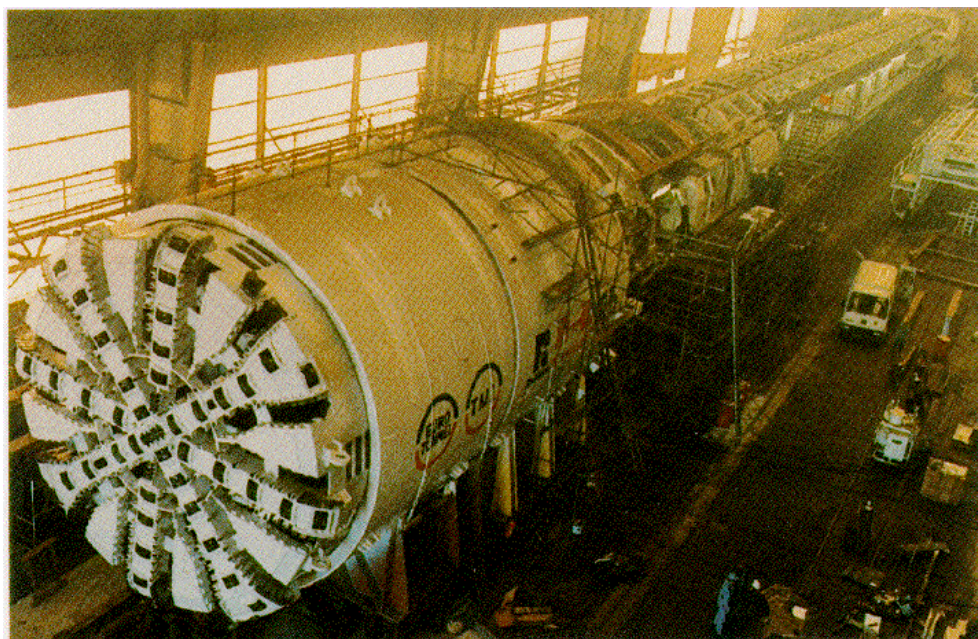
service tunnel as a pilot tunnel by probing ahead of the TBM, to locate: water bearing fissures, site investigation boreholes, deep weathering, and proximity of Grey Chalk/Gault Clay/Fosse Dangeard fault.

On the UK side, grout injections through holes drilled from the marine service tunnel improved conditions ahead of running tunnels TBMs, producing a 3 m annulus of treated ground at the upper half of both tunnels. It had to be carried out with minimum interferences. It proved to be successful since the average rates increased from 85 m/week to 210 m/week in the treated ground.

In France, overlapping destructive probe holes were drilled from the face of T1 (marine service tunnel), to give advance warning of unstable ground and high or saline water inflows. Micropalaeontological examination of the returns was used to determine the level of the Chalk Marl. Detailed geotechnical logs were made of the side walls and (where possible) at the front. The water inflow proved to be considerably lower than the specified values (7 l/s/km for RTs, 6 l/s/km for ST).

High boring rates

The best rates achieved in 30 consecutive days, were, in dry ground: 1,716 m (UK land south running tunnel), and in waterbearing ground: 1,232 m (French south running tunnel).



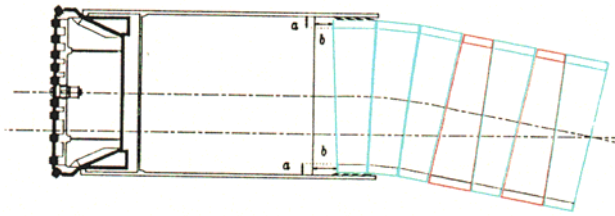
TBMs on French Side		Service Tunnel		Running Tunnel North/South	
		Sea (T1)	Land (T4)	Sea (T2/T3)	Land (T6/T5)
Manufacturer		ROBBINS	MITSUBISHI	ROBBINS/ KAWASAKI	MITSUBISHI
Excavated Diameter	m	5.77	5.61	8.78	8.64
TBM length	m	11	10.6	13.75	12
Total length TBM+backup	m	318	204	265	211
Backup cars	units	19	13	16	14
TBM weight	T	470	350	1250	600
Backup weight	T	600	400	800	400
Max Thrust on head	T	1800	4000	2000	9000
Max back thrust	T	4000		11500	
Max torque	Tm	360	400	1300	1300
Max installed power	KVA	2700	2500	4000	3800
Rotating speed	RPM	2.5 or 5	0.9 or 1.8	1.5 or 3	1 or 2
Max boring rate (instant)	cm/mn	12	8	12	8
BORING RATES					(T5 data)
Final chainage planned	m	13800	3251	16270	3265
" " reached	m	15618	3251	20009/18860	3265
Works duration	days	975	304	911/825	324
Boring duration	days	774		781/742	225
Daily average	m/day	20.2		25.3/25.4	14.5
Best day	m	56		52.8/54.5	49.6
Best 7 days	m	300	210	306/322	253
Best 30 days	m	1062	887	1124/1232	847

Innovating approach on French Side

Many refinements have been found, in positioning of cutting-head tools as well as in operating the machines. Anticipated progress rates have been considerably

exceeded in France, leading to increase the original excavation length **by 8125 m**.

TBM T4 (French land service tunnel) achieved **837 m** in the waterbearing zone under a pressure of **3 bar**. TBM T1 (marine



Above : "Pinched" rings on French side allow to bolt and seal the rings, and contribute to TBM steering : while following curves, rings are kept in contact. Straight drive, vertical or horizontal curves are achieved by rotation of the ring around tunnel axis (for example, red "key" segments are not in the same position than the blue ones). Right : Service tunnel with temporary tunneling fixed equipment on UK side (above) compared with French side (below, and also cover page). In UK, the temporary track is ballasted; the key segment of each ring is at a fixed location, and lining is unbolted. In France, temporary track is installed on metal frame; the key segment is at different locations on two adjacent rings; bolt boxes are visible on each segment.



service tunnel), T2 and T3 (marine running tunnels) reached a final **daily rate over 50 m**, following a slow start of T1 in difficult ground, but using the experience gained in the service tunnel to optimize T2 and T3.

Air cushions allowed to turn the land TBM T5, renamed T6, back to Sangatte. Only 16 Tonnes of traction were needed instead of dismantling/displacing a 600 T TBM.

Lining

Lining was the critical operation that dictated tunnelling progress.

UK side:

Service Tunnel machines were designed for a cycle of 18 min, and 22.5 min for running tunnel machines. The lining was a precast concrete unbolted wedge block with pads on the extrados to allow for a 20 mm grout layer. There were 7 segments per ring in the service tunnel and 9 segments per ring, all different, in the running tunnels, with a thickness varying depending of the overburden, from 54 cm (land), to 27 cm (sea, from 0 to 7 km to the shore) or 36 cm (sea, over 7 km from the shore). The placing of segments was considerably altered when the stability of the ground was not adequate.

French side:

The main design constraint was waterproofing with hydrostatic water pressure up to 11 bars. Complex numerical models were used - in addition to the convergence-confinement method - to evaluate the interaction between tunnels, the influence of the proximity of a Gault Clay layer, and the quality of grouting behind the segments. Optimization studies led to adopt a high-performance concrete (80 to 100 MPA) and different types of reinforcement. **"Pinched" rings** allowed the lining to follow the curves, by rotating the position of the ring into 4 possible locations.

Contrarily to the UK side, the French Tunnels were lined with bolted precast concrete segments erected within the shield. Five main segments (8 tonnes, 40 cm thickness) plus a key formed a complete

ring of 1.6 m wide for running tunnels.

These six components arrived at the tail-end of the backup train and were lifted by an overhead conveyor. They were moved by vacuum lifting arms to one of two independent vacuum erectors, which installed them into position. The designed cycle was about 30 minutes but rings could be placed in 15 minutes.

In « open » mode, it was possible to erect segments during excavation, the TBM pushing against the ground by means of lateral grippers. In « closed » mode, excavation and placing of segments could not be done simultaneously.

Grout is injected afterward in the 15 cm gap between segments and ground, about 300 m behind the TBM head. It consists of two components prepared on surface (retarded sand mortar, aluminous cement slurry). The 10 cm gap between the tail of the pressurized chamber and the concrete lining rings was sealed by grease injected into four rings of metallic brushes inside the TBM shield.

Breakthrough

Service tunnel

Once the TBMs surveyed after stopping at 100 m distance, a corrective line allowed a further 50 m drive of the UK TBM, while the French TBM was being dismantled. The UK machine was then turned aside on a tight curve and buried, the remaining being excavated using hand-held tools (for a small adit dedicated to the historical

breakthrough), and then roadheaders.

Running tunnels

Junctining was achieved by diverting each UK TBM downwards below floor level (vertical curve, radius 300 m) and driving the French TBM through to meet the last UK permanent lining. Ground support included temporary segments in the invert, and shotcrete and fibre-glass rockbolts over the crown. Once the British TBM below the permanent line, it was backfilled with low strength concrete (about 2,000 m3). British lining was then extended through the remaining skin of the French TBM once dismantled.

150 km of tunnels have been built, 24 h a day, on both sides in less than 3.5 years (4th Jan.1988 to 28th June 1991).

Left : The historical first undersea breakthrough (service tunnel, 1st of december 1990). Right: Last breakthrough (28th of June 1991): French TBM T3 reaches UK cast iron segments, in running tunnel south undersea.



TML, THE CHANNEL TUNNEL CONTRACTOR, IS A JOINT VENTURE BETWEEN: Balfour Beatty constructions LTD, Bouygues S.A., Costain Civil Engineering LTD, Dumez S.A., Société Auxiliaire d'Entreprises S.A., Société Générale d'Entreprises S.A., Spie Batignolles S.A., Tarmac Constructions LTD, Taylor Woodrow construction holdings LTD, Wimpey major projects LTD.

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