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# The Channel Tunnel:
# Construction and The Marine Service Tunnel Breakthrough

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**SUMMARY:** This paper provides an overview of how the Channel Tunnel project was accomplished. The emphasis is on construction of the tunnel system. The main aim is to illustrate the magnitude and complexity of the overall task so that the various remarkable achievements of the project, especially in the areas of logistics and surveying, can be recognised. Following a description of the Eurotunnel twin bore "Rolling Road" system, the geological and geotechnical features of the tunnel are described. The various construction methods and the overall construction programme are then outlined. The construction of the Marine Service Tunnel is then detailed, including tunnel boring machine operation, survey control, and the breakthrough and junctioning procedures.

## 1 INTRODUCTION

[The reference used in this section was Irwin (1)]

The Channel Tunnel is one of this century's largest and most ambitious civil engineering projects. Testament to this fact is that it was voted the greatest construction achievement of the 20th century by construction engineers around the world, beating Chek Lap Kok airport in Hong Kong, the Panama Canal, and 97 other nominations for the award. The announcement was made at the Conexpo exhibition in Las Vegas (one of the largest construction meetings in the world) in March 1999 and was the result of a poll made by readers of an array of construction magazines. Its technological achievements and utility surpassed the others, they said.

In addition, in 1997 the American Society of Civil Engineers voted it one of the seven modern wonders of the world.

This paper provides an overview of how the Channel Tunnel project was accomplished. The emphasis is on the construction of the tunnel system, concentrating on the role of the Marine Service Tunnel. The main aim is to illustrate the magnitude and complexity of the overall task so that the various remarkable achievements of the project, especially in the areas of logistics and surveying, can be recognised.

## 2 BACKGROUND TO THE EUROTUNNEL PROJECT

[Unless stated otherwise the references used in this section were Henderson (2) and Essig et al (3)]

### 2.1 Selection of the Fixed Link Scheme

The construction of a tunnel under the English Channel has been proposed at various times over the last 200 years. In 1974 4.3km of tunnel was driven from England to demonstrate the ideal mechanical boring conditions that exist in the ground beneath the Channel. With cross-Channel traffic on the surface and in the air heavily congested and a move towards decreasing trade barriers within the European Community; the British and French Heads of Government announced their enthusiastic support for a privately funded fixed link on the 30th November 1984.

In response to an Invitation to Promoters, four projects were tendered. The competing schemes included bored tunnels, submersed tubes, artificial islands and bridges; and embraced both rail and road transport solutions.

On the 20th January 1986 the two Governments decided on the Eurotunnel Scheme because:

- it was the soundest financially;
- it carried the fewest technical risks;
- it was the safest for the traveller;
- it presented no navigational hazard;
- it was the least vulnerable to terrorist action; and
- its environmental impact could be contained.

### 2.2 Parties to the Project

A concession agreement signed on the 14th March 1986 gave the Eurotunnel promoters, a consortium of banks and construction companies, 55 years from the 29th July 1987 to construct and exclusively exploit the rail link.

After the concession was awarded the promoters formed two separate organisations. Eurotunnel was established as the concessionaire to own and operate the system and raise the necessary finance of £6billion (~$A12billion in 1986).

Transmanche Link (TML) was formed as the contractor. This was an umbrella organisation for the purposes of liaison and coordination between the UK and French halves of the project. Each original group of five construction firms formed their own joint venture: Translink JV in the UK and Transmanche Construction GIE in France.

### 2.3 Progress of the Project

Work began in May 1986 and the fast-track design-and-construct program called for a construction period of seven years with a completion date of May 1993.

The project was plagued by cost, schedule and safety problems and consequently took eight years to complete. At a final cost of £9billion it became one of the world's largest privately financed engineering endeavours. [Irwin (1)]

It is interesting to note that the civil works were completed to program (although not to budget), the overall project time overrun being mainly due to problems with commissioning the incredibly complex control systems.

## 3 THE EUROTUNNEL SYSTEM

[The main reference for this section was Crighton et al (4)]

- The Eurotunnel system is a twin bore rail tunnel for "Rolling Road" shuttles and through trains.
- From portal to portal the tunnel system is 50.5 km long, 37.9km of which are under the sea.
- The two 7.6m internal diameter running tunnels (one for each direction of travel) are 30m apart and straddle a central service tunnel of 4.8m internal diameter (See Figure 2).
- Access cross passages of 3.3m internal diameter link the running tunnels to the service tunnel at 375m centres (See Figure 2)
- 2m internal diameter piston-effect relief ducts connect the running tunnels at 250m centres (See Figure 2).
- Two crossover chambers approximately 160m long x 20m wide x 15m high, at the third points, are required for single track working during maintenance periods and emergencies.
- Numerous signalling rooms, electrical substations and equipment rooms of 3.3m - 4.8m internal diameter are located throughout the tunnel system.
- There are three distinct low points on the alignment, each of which has a pumping station. Additional pumping stations are located at the coasts, to prevent any seepage flow from the under-land tunnel sections entering the undersea sections.
- Terminals at each end provide the road-to-rail interface and a loop section that connects the two running tunnels. The French terminal covers 470ha while the smaller UK terminal occupies 170ha.

## 4 TOPOGRAPHY, GROUND CONDITIONS, TUNNEL ALIGNMENT AND STRUCTURE SITING

[The main references used for this section were Crighton et al (4), Destombes et al (5), Missoffe (6), Eurotunnel (7), Biggart et al (8) and Fermin (9)]

### 4.1 Site Investigation History

The possibility of a fixed link between Great Britain and France has led to the geology of the Dover Strait being given considerable attention for over a hundred years. Samples of the seabed were taken between 1872 and 1883, further work was carried out in 1958-59 and a major site investigation in 1964-65 included nearly 100 marine boreholes, 20 land boreholes and a thorough seismic survey at sea. Further work was also carried out in 1972-74.

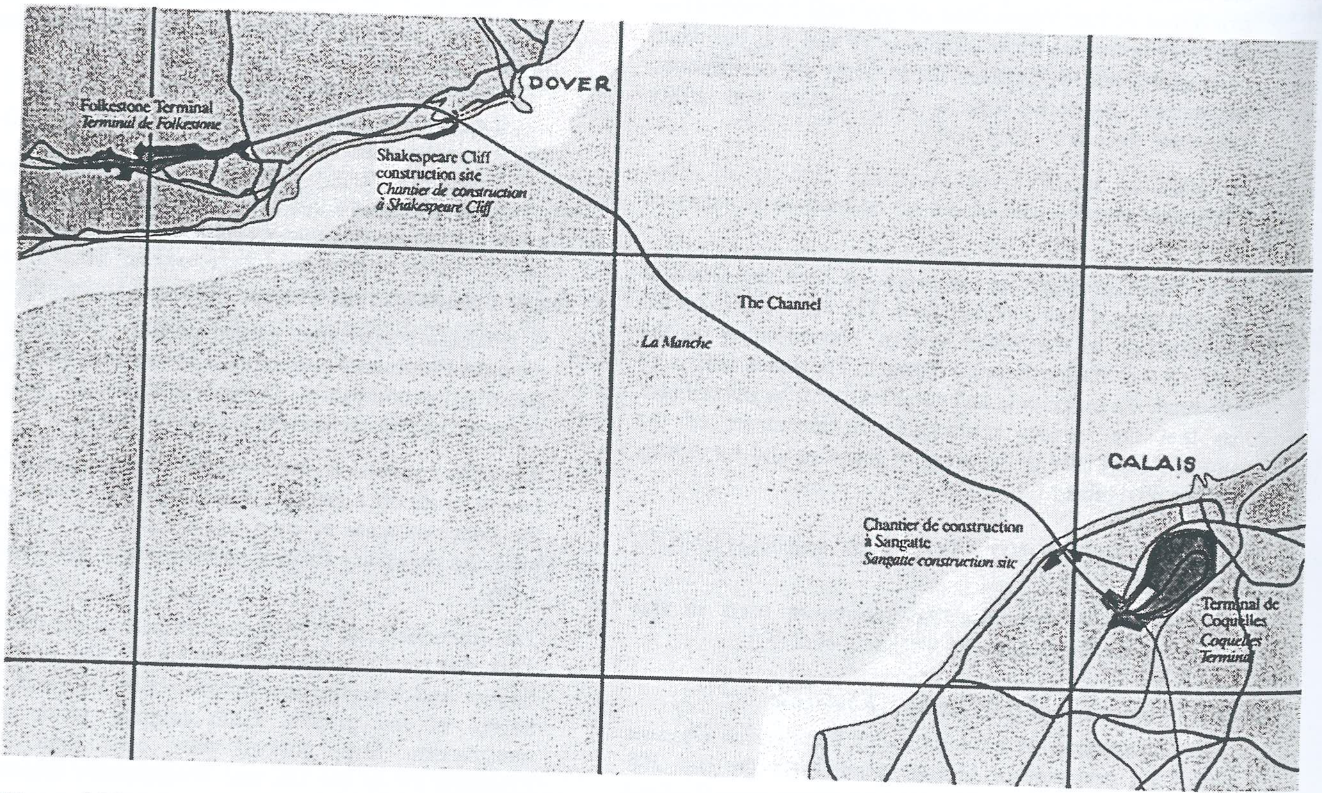

**Figure 1 The Eurotunnel System route, showing inland terminals and coastal construction sites.**

Recent geotechnical and geophysical surveys were carried out in 1986 and again in 1988. The main objectives were to supplement existing information, particularly in areas where significant changes were made to the alignment from previous schemes; and to gain detailed site specific information at the location of the crossovers and the Fosse Dangard (a major alluvium-filled erosional valley near the centre of the main channel).

### 4.2 Topography and siting of the Terminals

The Dover Strait is an erosional channel some 37km wide running approximately SW-NE. The maximum water depth is around 60 metres near the middle. The cliffs along each coast attain heights of between 50 and 75 metres at the neck of the Strait between Dover and Calais.

On the British Coast the ground rises towards Folkestone where the cliffs are up to 160 metres high. Consequently, the only relatively level area suitable for a terminal site is at the head of an erosional valley to the north west of Folkestone, about 13km west of Dover (See Figure 1).

On the French side however, the land flattens out almost immediately inland from the coast. Consequently a suitable site for the main terminal, two and a half times the area of the Folkestone site, was found just 3km south west of Calais (See Figure 1). This larger facility includes the rolling stock maintenance workshops.

### 4.3 Geology

The geological structure of the region comprises a Palaeozoic basin on which is superimposed an anticline of Cretaceous and Jurassic sedimentary beds. The major axis of the anticline is roughly at $90^0$ to that of the Strait, ie running SE-NW. Dover and Sangatte are to the east of the anticline, so that due to erosion, successively older rocks outcrop on the seabed as one progresses westwards. The upper beds of the Cretaceous system in descending order from the seabed are the Upper, Middle and Lower Chalk, Gault Clay and Lower Green Sand. Only the Lower Chalk remains beneath the seabed at the line of the tunnel. It is further subdivided into White Chalk (15-25m thick), Grey Chalk (15-28m thick), Chalk Marl (20-35m thick) and a thin layer of Glauconitic Marl. Further secondary anticlinal structures, running perpendicular to the main anticline, cause the strata to dip severely at the French coast. Some faults were identified within the French tunnel section. One substantial one caused deep penetrative weathering within the Grey Chalk, but this was not expected to penetrate to tunnel level within the Chalk marl. (See Figure 2)

### 4.4 Geotechnical Properties

The White and Grey Chalks, carbonate content 85 and 80 per cent respectively, are of relatively hard, brittle and fractured material. Flint, which is very hard, is generally found in the Middle Chalk but was expected in the upper layers of the Lower Chalk as well.

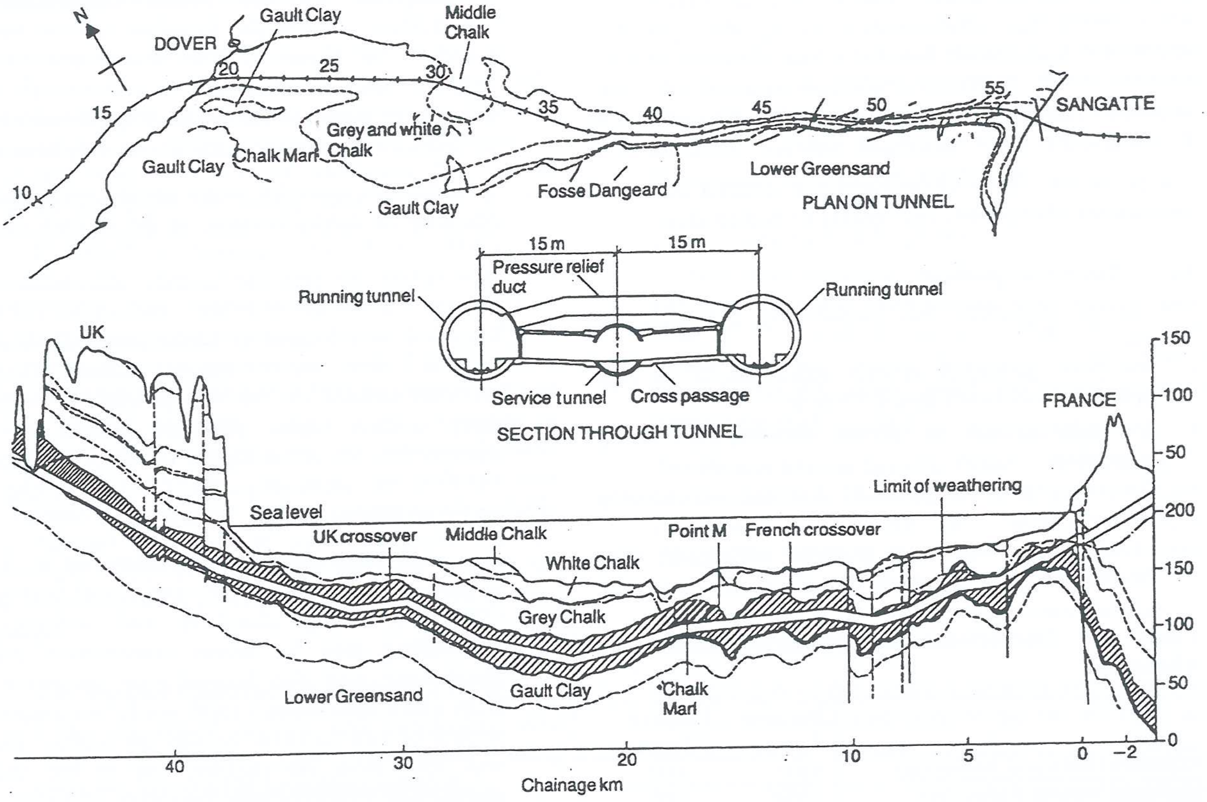

Figure 2 Geological plan and cross-section, and section through the tunnel system.

**Table 4.4 Geotechnical Properties of the Lower Chalk and Gault Clay**

| | Compressive Strength (MPa) | Deformation Modulus (MPa) | Permeability (m/s) |
|---|---|---|---|
| Weathered White Chalk | 7 –11 | N/A | $5 \times 10^{-5}$ |
| Sound Grey Chalk | 8 – 15 | 4700 | $1 \times 10^{-5}$ |
| Chalk Marl | 2 - 50 | 1300 – 2000 | $2.5 \times 10^{-7}$ - $1 \times 10^{-6}$ |
| Glauconitic Marl | 6 – 35 | N/A | $1 \times 10^{-7}$ |
| Gault Clay | 1 – 4 | 350 | $1 \times 10^{-7}$ |

The Grey Chalk was estimated to have 3-5 discontinuities per cubic metre, with thicknesses in the order of centimetres and marked chemical degradation in the upper parts. The estimated ingress per metre length of tunnel was 2 L/s for weathered Chalk reducing to 0.5 L/s for sound Grey Chalk. This renders the Grey Chalk highly aquiferous but with no risk of solution cavities.

The Chalk Marl, is a mixture of clay and carbonate-mudstone with an average carbonate content of 70% and moisture content of 11%. It is of low strength, homogeneous and slightly plastic, but retains a brittle mode of failure. It was considered to be essentially impermeable with 1-2 discontinuities per cubic metre, in the order of millimetres and generally filled with calcite, giving an estimated tunnel ingress per metre length of 0.1L/s.

The underlying Gault clay, while also virtually impermeable, is weaker than the Chalk Marl and exhibits strongly plastic behaviour leading to non-uniform time-dependent deformation when stressed. It is also subject to swelling action when exposed to water.

The permeable Lower Green Sand is a complex system of alternations of clay beds and weakly cemented sand.

## 4.5 Tunnel Alignment

The tunnel alignment was dictated by the following criteria:

- the basic geometric criteria applicable to a high speed railway (see Table 4.5 below);
- the minimisation of power consumption during operation;
- the establishment of optimum drainage and pumping regimes; and
- to be located as far as possible within the most favourable tunnelling medium.

**Table 4.5 Operational Design Criteria for the Alignment**

| | Running Tunnels | Service Tunnel |
|---|---|---|
| Minimum Horizontal Radius (m) | 4200 | 1000 |
| Minimum Vertical Radius (m) | 15000 | 1000 |
| Maximum Gradient (%) | 1.1 | 3.5 |
| Minimum Gradient (%) | 0.18 | 0.18 |

The Chalk Marl was considered to be a medium ideally suited to mechanised tunnelling techniques: easy to excavate yet competent with a good stand-up time suitable for the use of an expanded unbolted tunnel lining. As a result 90% of the tunnel's alignment is in the Chalk Marl at a depth at mid channel of approximately 115m below sea level and a cover of 70m, reducing to 19m near the French coast. Here, due to the dipping of the strata, the alignment goes through the upper beds of the Lower Chalk and then into the Middle Chalk to reach the inland portal at Beussingue, which is 3 km from the coast. On the UK side the tunnel alignment essentially stays within the Chalk Marl all the way to the portal on the western side of Castle Hill, 9km from the coast.

The tunnel profile is dictated by that of the strata: an elongated triple U. Similarly the plan alignment of the undersea section of tunnel follows the major axis of the Cretaceous anticline: i.e. a line running SE-NW. To remain in the Chalk Marl the alignment runs parallel to and about 3-4km to the west of a line linking Dover and Calais. Inland from the UK coast, it then swings round to the west and heads directly for the terminal. In France the portal remains on roughly the same NW-SE line as the undersea alignment. (See Figure 1)

## 4.6 The Tunnel Construction Sites

In order to reduce the length of the tunnel construction programmes, construction was to be carried out concurrently on two fronts, on both sides of the channel. Tunnelling would commence from a single location, but proceed both seaward and landward. In addition it was advantageous for the tunnel commencement and construction support site to be as near to the coast as possible (See Figure 1). This was in order to keep the length of the seaward drive to a minimum. The reason for this was to minimise the logistical problems of supplying an undersea construction face from a very long distance.

Providing the space for such a major construction site and reaching the tunnel horizon, in the vicinity of the White Cliffs of Dover presented a formidable challenge. Fortunately the task had already been achieved by the Service Tunnel demonstration project in 1974. A split-level site was located at Shakespeare Cliff, about 3km west of Dover. The site offices, canteen, change rooms, etc were situated on the high ground above the cliff. A steep decline tunnel provided access to the main construction site at the foot of the cliff. A further decline led from this sea-level platform to the existing 4.3km of undersea Marine Service Tunnel.

A second, larger decline was constructed to provide rail access to what were initially the tunnel-boring machine (TBM) launching chambers and subsequently the marshalling area for tunnel construction traffic. The marshalling area also housed spoil collection bunkers, from which each tunnel's spoil would be transported to the surface by belt conveyor through the original adit. A shaft was sunk from the cliff-top site to the underground marshalling area to provide personnel access to the tunnel system.

On the French side the fractured aquiferous nature of the weathered ground, rather than the topography of the site, presented the obstacle to reaching the tunnelling horizon. In this case a huge access shaft, 55m in diameter and 65m deep, was sunk at Sangatte about 4km west of Calais.

## 5 CONSTRUCTION OVERVIEW

[The references used in this section were Crighton et al (4) and Biggart et al (10)]

### 5.1 Implications of the Geotechnical Investigations

By 1988 the Channel Tunnel area had probably become the most thoroughly investigated site ever. To be able to carry out a site investigation, the aim of which is to confirm and supplement a hundred years worth of exisiting information is unprecedented. This situation provided a high level of confidence in the knowledge of the ground conditions, of what was essentially a straightforward geological structure.

Consequently the design of the underground structures and the selection of the construction technique could be accurately tailored to the local conditions, allowing a high level of efficiency. In any other situation a conservative all encompassing approach would probably have been employed due to the lack of familiarity with the ground conditions.

An example of the successful use of this approach occurred when the type of TBM for each of the tunnel drives was selected. Closed face Earth Pressure Balance (EPB) machines were selected for the French drives to deal with the waterladen fractured ground near the coast. This technology although expensive is well-proven and reliable in bad ground conditions. On the UK side on the other hand, fissured water-bearing ground was only expected in isolated instances. In this case open face (i.e. at atmospheric pressure) machines were employed in conjunction with a method of confirming the ground conditions ahead of the tunnel face, so that ground treatment contingencies could be employed if required.

In addition, the level of confidence in the structural quality of the Chalk Marl presented the opportunity to introduce a construction technique that had previously not been used in soft rock applications in the UK. The New Austrian Tunnelling Method (NATM) provided a fast and efficient method of constructing one-off structures or structures whose cross section was not uniform. Initially trialled and confirmed on the marshalling area development works, which comprised fairly straightforward structures, it was then applied to the construction of the UK Crossover chamber, one of the most ambitious underground chambers ever constructed in Europe.

### 5.2 The Various Construction Methods Employed

- All the UK tunnel horizon and marshalling area development works were constructed using roadheaders and NATM tunnelling methods.
- The French shaft at Sangatte was constructed using diaphragm wall techniques.
- For the most part the tunnels were constructed using TBMs: open-face machines on the UK side and EPB machines on the French side.
- There is a half kilometre section of cut-and-cover tunnel at Holywell Combe just east of the UK tunnel portal.
- Between Holywell Combe and the UK portal there is a half kilometre section through Castle Hill that was constructed using road headers and NATM techniques.
- The UK Crossover chamber was constructed using NATM techniques with roadheaders and excavators.
- The French Crossover chamber employed the parallel drift method of construction.
- Ancillary structures such as the cross passages, piston effect relief ducts and pumping stations were all constructed using hand held pneumatic equipment and lined with cast iron segments.

### 5.3 Spoil Disposal

The 4.3 million cubic metres of UK spoil was used to reclaim the site at the foot of Shakespeare Cliff from its original 5 hectares to a final area of approximately 30 hectares.

The 3 million cubic metres of French spoil was slurried and pumped to a purpose built settling lagoon 1 km from the Sangatte site.

### 5.4 Precast Concrete Lining Manufacture

The precast concrete segments used to line the tunnels were manufactured by two purpose built facilities. In France, the main tunnel construction site at Sangatte was large enough to accommodate their plant. In the UK however, limited site space necessitated the construction of a plant on the Isle of Grain in the Thames estuary. Granite aggregate was shipped from a dedicated quarry in Scotland and the segments were transported to the Shakespeare Cliff Lower Site by rail.

### 5.5 Construction Logistics

On both sides tunnelling by TBM commenced at the coast and proceeded both seaward and landward. Therefore, a total of 12 tunnel drives were required. The shorter French landward running tunnel drives were constructed using the same machine, which was turned around in the Beussingue portal cutting.

The French Marine Service Tunnel TBM was the first to be launched from the Sangatte shaft, in March 1988, and maintained a 10 month lead over the running tunnel TBMs (See Figure 3). This was so that ground conditions could be confirmed ahead of them, and to meet the UK marine Service TBM for the initial breakthrough in order to close the survey traverse.

Construction of the French Crossover and other ancillary structures commenced towards the end of TBM activity (See Figure 3).

### 5.6 The Strategic Role of the UK Marine Service Tunnel Drive

The UK Marine Service Tunnel began on January 1st 1988, nearly a year ahead of the UK running tunnel machines and maintained a 10km lead for the following reasons (See Figure 3).

#### 5.6.1 Ground Treatment

The Service Tunnel acted as a pilot tunnel, to investigate and confirm ground conditions and provide enough time for any necessary treatment to be carried out so that running tunnel progress was not affected.

The necessity for ground treatment arose just off the UK coast where fissured water-bearing ground was encountered. A fan of holes was drilled and a silica based cement grout was injected to provide a protective hood over the path of the running tunnels.

#### 5.6.2 Excavation of the Crossover Chamber and other Ancillary Structures.

The Marine Service Tunnel provided the access and supply route for construction of the UK Crossover chamber. This was in order to construct the Crossover chamber before the arrival of the running tunnel machines. Similarly most of the ancillary structures that were excavated by hand were constructed from the Service Tunnel.

#### 5.6.3 Initial Breakthrough

The French Marine Service Tunnel drive began soon after the corresponding English tunnel drive was begun; so the two drives had the distinction of making the initial contact for their country's construction team, providing the opportunity to close the two survey traverses.

## 6 CONSTRUCTION OF THE MARINE SERVICE TUNNEL BY TBM

[The main references for this section were Biggart et al (10) and an unpublished TBM operator's manual written by James Howden & Company, Scotland]

### 6.1 Operation of the UK Open Face TBM

The 15m long main body or "shield" of the Marine Service Tunnel TBM had two sections, which moved telescopically relative to each other. When advancing, the cutting head section thrust off the gripper section. The cutter head rotated at a top speed of 4.5rpm. There were 16 thrust rams each normally delivering 90t; that is a total thrust of 1440t. There were 270m of trailing backup gantries and the total weight of the TBM was 700t. The following is a description of one production cycle:

- The machine pulls up its gripper section and trailing backup gantries after having just completed a 1.5m long cut.
- A pre-cast concrete ring of 6 segments is built in the exposed tunnel bore. A wedge key is thrust into the ring to expand it and lock it against the excavated ground.
- Cementitious grout is pumped behind the ring to create a uniform contact service between the ground and the concrete lining and to stop any water flow.
- During ring building an empty skip train is positioned under the conveyor discharge of the TBM.

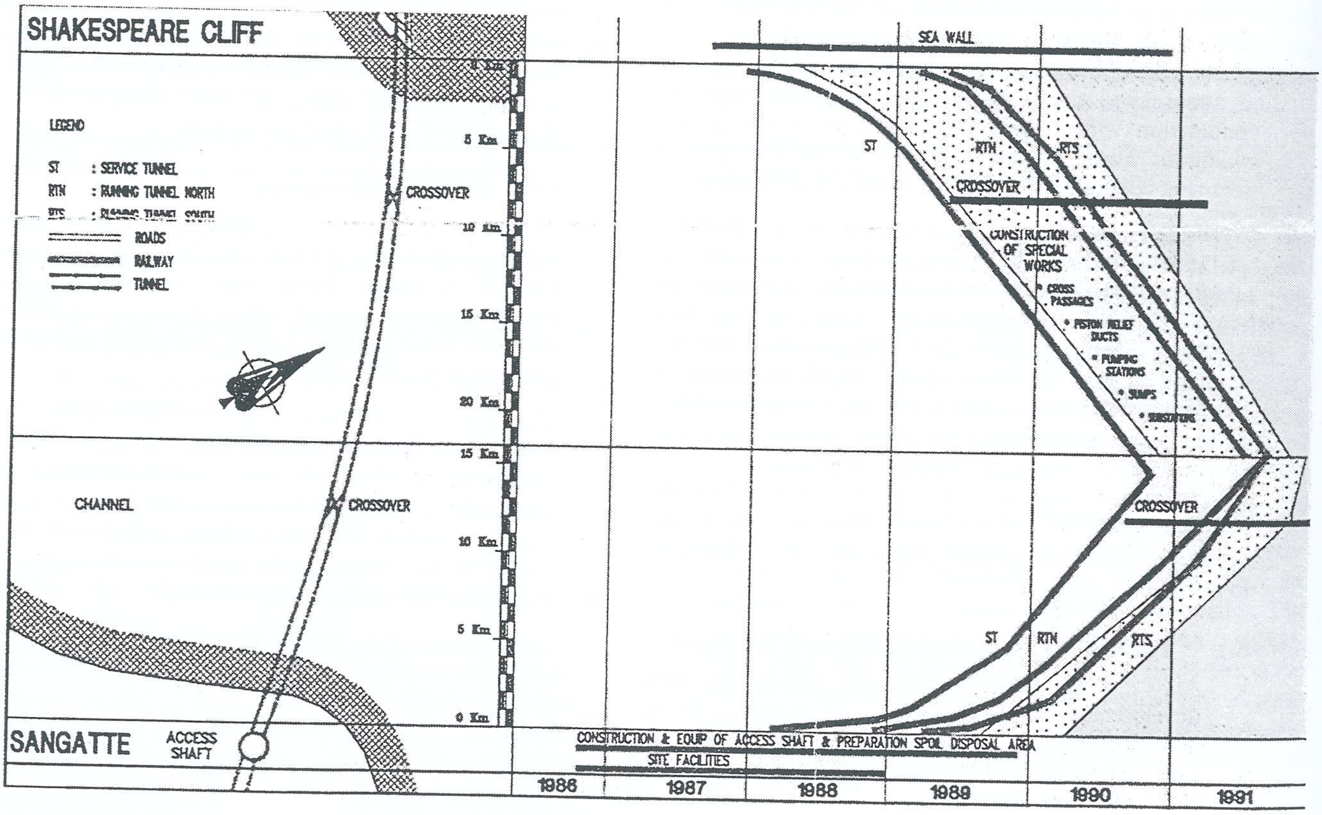

**Figure 3 The undersea works construction programme**

- A new cut is commenced. Spoil is transported from the head to the muck skips by conveyor belt.
- The cycle repeats.
- Each train brings in the lining segments and takes out the spoil, for 1 production cycle.
- The rate of advance is 1.5 m in about 40 min.
- Best day 60 m.
- Best month 1.04 km.

It was necessary to investigate ground conditions ahead of the open face TBM. Every week a 250m destructive probe hole was drilled to determine the water bearing state of the ground. Also, vertical core samples were taken near the low point of the alignment to determine the distance to the underlying unfavourable Gault Clay.

If a potential inundation situation was encountered, the muck conveyor could be retracted from the head very quickly and a trap door automatically sealed the face off. In addition, a circumferential blade seal could be thrust out into the ground to seal off the annular space (provided for manoeuvring) between the shield and the excavated ground.

### 6.2 Operation of the French EPB TBM

The French earth pressure balanced machine had similar characteristics to, and operated in much the same way as, the UK open-face machine except that it was designed to operate in full static head conditions, which reached a maximum of 95m of water. The TBM main body acted as a pressurising piston against the ground water. The cut spoil was ground up and mixed with the water to create a paste plug within the cutter head. The spoil was evacuated from the head by Archimedian screw and then transferred to the skips by belt conveyor.

The pre-cast concrete segmental lining was bolted together within the tail skin of the shield. Seals at the end of the tail skin prevented water ingress into the shield. When the TBM advanced the ring was left behind in the tunnel bore. Grout was then placed behind it.

The French EPBs were able to operate in either closed or open mode, depending on the present water content of the ground. In open mode the gripper section was used, to thrust against. In closed mode the ground conditions were usually such that the shield had to thrust off the concrete lining.

## 7 SURVEYING TECHNIQUES & TUNNEL ALIGNMENT CONTROL

[The main reference for this section was Winney (11)]

### 7.1 Primary Control Network

Overall primary control for the entire site was based on a network of sightings across the channel established over many years with recent input from a satellite global positioning system (GPS). A rectangular grid based on a transverse Mercator projection, with its central meridian near the middle of the project, was used to convert from a curved geodetic co-ordinate system to a planar rectangular one.

A local network of survey stations was established at both coastal sites, to transfer the primary survey underground. On the UK side, at Shakespeare Cliff, this included a traverse running through the two adits to the enlarged marshalling area of the service tunnel, where the baseline for the tunnel primary traverse was established. At Sangatte in France the corresponding transfer underground was done by taking a series of steeply inclined theodolite sights down the access shaft. This produced a very short baseline from which to extend the primary traverse.

### 7.2 Tunnel Control Traverse

The primary traverse was extended down the tunnel using a 75m zigzag pattern with wall-mounted stations on alternating sides of the tunnel. This method enabled the systematic error due to refraction, introduced when taking sights along one side of the tunnel, to be effectively cancelled out. The refraction is caused by a temperature gradient along the tunnel radius due to warm air from the face flowing through a tunnel whose concrete lining is damp and cool. If not accounted for, this phenomenon would have put the tunnel on a 3000km radius, which would have resulted in the UK drive being off line by several diameters after the 22 km of drive towards France.

Settlement of the lining as the ground loading came on meant that revisions to the zigzag survey were required to account for the 5mm to 10mm spread of the tunnel lining.

A second separate traverse was carried forward on tripods along the tunnel invert to provide a check of the zigzag traverse.

Weaknesses introduced into the primary traverses, by both short baselines and refraction, were picked up by check sightings with high-precision north-seeking gyro theodolites. These instruments were able to provide a true reading of azimuth anywhere in the tunnel.

On several occasions a separate traverse was carried out by a German team in order to provide a completely independent check on the in-house primary traverse.

### 7.3 Production Traverse

A separate production traverse was carried forward along one side of the tunnel only, by the TBM shift engineers. This traverse was used to set out laser stations for machine guidance. On a regular basis the primary survey team would extend their control traverse into the TBM and pickup the production traverse stations. The co-ordinates of these stations were then adjusted accordingly.

### 7.4 Tunnel Alignment Control

The information used to steer the TBM is provided by a laser-guided system:

- The laser is set out parallel to the Designed Tunnel Axis (DTA).
- On curves the laser defines a chord and is taken around the curve using a Prism Beam Deflector.
- The "ZED" onboard computer guidance system is fed with a data set of points (coordinates) that define the DTA and information describing the position and orientation of the laser.

- An electronic target on the TBM picks up the laser spot. The computer can then calculate the position of the machine.
- The machine's actual position is then compared with that of the DTA at the present chainage.
- "Off" line and level information is displayed in the operator's cab.
- The operator steers to reduce these figures to zero by individually selecting thrust rams.

## 8 BREAKTHROUGH AND JUNCTIONING PROCEDURE OF THE MARINE SERVICE TUNNEL

[Unless stated otherwise the information for this section was taken from unpublished internal TML design and construction documents.]

### 8.1 Desired Criteria for the Breakthrough Procedure

The two Marine Service tunnel drives were of unprecedented length, undersea and between separate landmasses. Therefore, the logistics of junctioning the two tunnels, including the safe disposal of the boring machines, were challenging in the extreme.

In addition, the precise relative position of the two tunnels would not be known until the separate survey traverses could be closed. The final design had to be capable of accommodating this potential variance whilst minimising the impact on the running tunnel alignments and associated structures.

Many schemes were suggested and several reports compiled on the best junctioning method. Some, like the one entailing the construction of a large cavern (similar to the crossover) in which all six machines could be preserved in an undersea museum, could only be described as fantasy. Others like the head on junction, cutting out one TBM and sliding the second into its place were wishful thinking. In practice, considering the issues mentioned above, this task would have become an engineering nightmare.

The "ideal" solution had to be:

- engineeringly practicable;
- capable of meeting the overall programme;
- cost effective;
- politically acceptable to both parties; and
- above all it had to be safe.

To achieve these criteria the following specific conditions were applied:

- The meeting point should not be predetermined and should be independent of the other tunnels.
- The scheme should not involve dismantling and removal of the TBMs.

This last condition however, was modified following discussions with specialist sub-contractors who confirmed that removal of all but the structural skin was both a feasible and safe option for the French TBM.

### 8.2 Solution Options

The development of the options concentrated on the construction of the junction and disposal of the TBMs irrespective of location. This was possible as the tunnel alignment in the likely area of the junctioning was of consistent plan and profile.

From the various schemes which were identified, 3 options were chosen which best met the objectives and warranted further analysis. A cost and programme comparison was then carried out to identify the most suitable proposal.

8.2.1 Option 1: Double curve; both TBM main-bodies buried; duration 14 weeks; cost £5.8M. (See Figure 4)

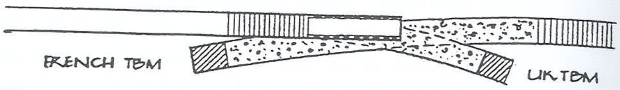

**Figure 4 Marine Service Tunnel Junction Option 1**

8.2.2 Option 2: Single curve; UK TBM main-body buried; French TBM main body stripped leaving the hollow shield; final Service Tunnel connection by manual heading into the French shield chamber; duration 9 weeks; cost £3.83M. (See Figure 5)

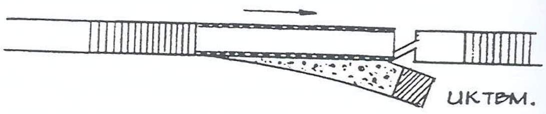

**Figure 5 Marine Service Tunnel Junction Option 2**

8.2.3 Option 3: Single curve; UK TBM main-body buried; French TBM driven towards the UK to complete the Service Tunnel; duration 12 weeks; cost £3.9M. (See Figure 6)

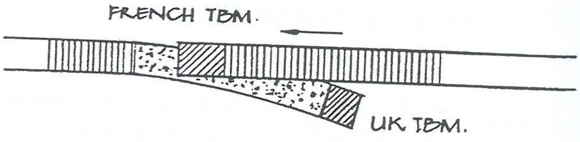

**Figure 6 Marine Service Tunnel Junction Option 3**

### 8.3 The Chosen Solution

Option 2 was clearly the cheapest and quickest scheme and is now presented in detail, as it happened (See Figure 7).

Phase 1

At the end of October, after driving 22km on the British side and 16km on the French side, the two machines were stopped with 100m separating them. A probe hole was drilled from the UK machine towards the French. It broke through into the French face on the 30th November 1990. A sophisticated Maxibor hole-surveying device (used for the first time horizontally in tunnelling and accurate to 1:1000) was used to determine the relative positions of the two tunnel drives. It was found that there was a horizontal

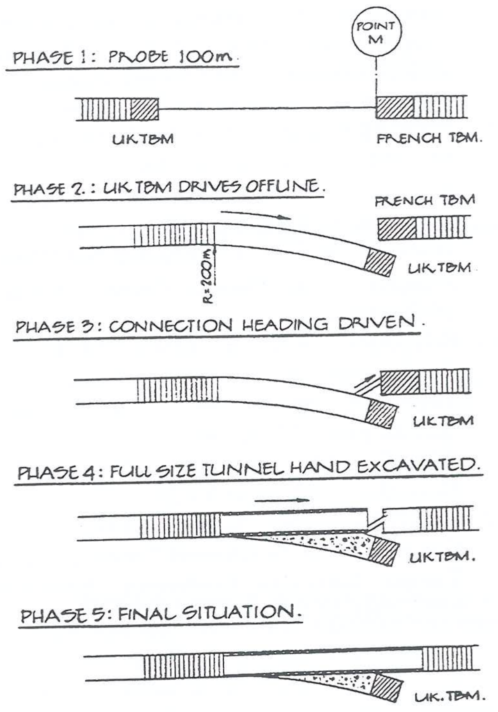

**Figure 7 Junction Option 2, phase by phase.**

misclose of 500mm (+/- 100mm) between the two headings. A level check was also performed with a water tube giving a vertical misclose of 50mm.

Phase 2

The UK TBM was then driven off the Service Tunnel alignment on a 200m radius curve, using a temporary lining to support the tunnel. Modifications to the TBM were necessary, as the minimum design radius of curvature for the Service Tunnel was 1000m. The TBM backup train was then disconnected from the shield, dismantled and removed from the tunnel.

Meanwhile, the French TBM backup train was de-coupled from the main body and withdrawn from the tunnel. The remaining shield was then gutted.

Phase 3

On the 1st of December 1990 a hand-dug adit from behind the UK shield broke through into the French shield chamber and parties from either side made the first land crossing of the Channel since the Ice Age. A conventional precise closure between the two survey traverses was also carried out, giving the following misclose details: horizontal 361 mm; vertical 58 mm; chainage 69 mm [Korritke (12)]

Phase 4

The offline UK drive was then backfilled with concrete, burying the TBM main body. The Service Tunnel was realigned by manual excavation from the UK end and lined with cast iron segments.

Phase 5

The tunnel was completed by extending the cast iron lining into the French TBM shield at the end of January 1991.

### 8.4 Discussion

Option 2 was clearly the cheapest and quickest scheme. It had the feature that UK and French operations were carried out independently until a very late stage in the procedure. This had considerable benefits in terms of coordinating operations and to a lesser extent in border control formalities. In particular, from a safety point of view, there were major advantages in containing and controlling fumes from French flame cutting operations during gutting of the shield.

Options 1 & 3 required a TBM to remain static for significant periods, which presented a considerable exposure to risk. For Option 2 the UK TBM was only temporarily stopped while probing, the breakthrough and surveying occurred. Options 2 and 3 involved stripping the French TBM, leaving the skin in place. Option 2 provided an advantage by allowing this exercise to commence at the earliest opportunity with some degree of programme float.

All three of the schemes allowed for the initial 100m probe hole in order to permit the low-precision closure of the survey traverses prior to the final TBM burial curve(s). This provided enough precision to ensure that the TBM that was being turned off on its burial curve would not hit its stationary counterpart. But, only options 2 and 3 allowed for precise closure before manually completing the remaining 100m of Service Tunnel. This course of action allowed the misclose to be gradually and subtly reduced over the full 100m length, rather than creating an obvious kink or step in the final tunnel alignment.

Once chosen, Option 2 was further refined to include the deviation of the southern running tunnel alignment to provide for an extra 3m separation distance required, between it and the Service Tunnel alignment, to accommodate the buried TBM.

## 9 CONCLUSION

In order to realise the vision of the Eurotunnel system significant achievements were made in almost every aspect of its design and construction. The milestone that epitomised the collective achievements of the Channel Tunnel project was the breakthrough of the Marine Service Tunnel on 1st December 1990. The UK Marine Service drive at 22km is the longest undersea heading ever accomplished. The French, after reaching the tunnelling horizon through extremely bad ground, drove 16km to link up with the UK drive.

In addition, the UK Marine Service Tunnel was of pivotal strategic importance to the UK marine-tunnelling programme, acting as a pilot tunnel for the main running tunnels and providing the access and supply route for the construction of the majority of the ancillary structures.

The fact that the overall production programme was met and the junctioning procedure was successful is testament to the outstanding logistic and surveying achievements of both construction teams.

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