

The channel tunnel engineering project



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The Channel Tunnel (French: le tunnel sous la Manche), widely recognized as one of the world's greatest civil engineering projects, is a 50.5 km underwater rail tunnel connecting Folkestone, Kent in the UK with Coquelles, Pas-de-Calais in France under the English Channel. Even though it began construction in 1988 and was opened in 1994, the idea to have a cross-channel tunnel was first mooted more than 200 years ago but did not materialize due to political, national security and cost considerations. However, with the tremendous increase in traffic growth, better and alternative means of communication, convenience and speed was necessary and hence the need for an alternative transport route was clearly evident. The need for such tunnel was further compounded with Britain joining the European Community and the cross-channel traffic doubling in the last 20 years (leading to the project), reflecting improved trading between the Britain and rest of Europe. The Channel Tunnel would also be able to provide an alternative competitive link between the transportation systems of the UK and France, providing both speed and reliability to freight deliveries. With the strong endorsement from the governments of both sovereigns, the decision to build the Channel Tunnel was thus made. In April 1985, the British and French governments issued a formal invitation to potential tenderers for the fixed Channel link and eventually the contract was awarded to the consortium Channel Tunnel Group Limited- France Manche S. A. (CTG/FM) (later renamed Eurotunnel).

The Channel Tunnel, with the governments' intention that it be privately funded and there would not be any government assistance or undertaking, was a build-own-operate-transfer (B-O-O-T) project with a concession. The

project organization is shown in Figure 1. In this contract arrangement, Eurotunnel would be the owner cum operator, which was being funded by the banks and shareholders. The governments of UK and France were represented by the Inter-Governmental Commission (IGC), to which the Safety Authority and the Maitre d'Oeuvre (an independent technical auditor) would report to. The IGC would then make final engineering and safety decisions. TML (essentially split from CTG/FM so as to separate the roles of owner/operator and contractor) consisted mainly of five British contractors (Translink Joint Venture) and five French contractors (G. I. E Transmanche Construction) and would carry out the construction works for the Channel Tunnel in a design and build contract. Upon completion of the project, the British and French governments would award Eurotunnel a 55 (which was later revised to 65) year operating concession to repay the banks and shareholders. The Contract was officially signed on 13 August 1986 and the fixed rail was to be fully commissioned in 1993. The services offered by the Channel Tunnel include the Eurotunnel Shuttle (a shuttle service for vehicles), Eurostar passenger trains and freight delivery trains.

TML's contract was to design, build, and test and commission the fixed rail tunnel. The Channel Tunnel (Figure 2) was designed to have three concrete-lined bores approximately 50km long, with 37.9km undersea and the rest under land at either ends of the English (Cheriton near Folkstone) and French (Pas-de-Calais village of Frethun) terminals (Figure 3). Two of the running tunnels were designed to have an internal diameter of 7.6m while the third was a 4.8m service tunnel running midway between the two and connected to them via 3.3m diameter cross passages at 375m intervals. 2m diameter

piston relief ducts connecting the main tunnels at 250m spacing were built to prevent the accumulation of differential air pressures and aerodynamic resistance. To facilitate operations and maintenance, four crossover caverns were built between the two terminals to allow trains to cross between the running tunnels. Two crossovers were laid close to the terminals while the other two were under the seabed, effectively dividing the tunnel into three approximately equal lengths. Figure 4 below shows the main phases of the project.

Two separate rail tunnels were chosen instead of a single large twin-track rail tunnel because this could minimize construction risk while at the same time enhance operations, maintenance and safety. The diameters were finalized after design analysis, development and optimization studies, taking into consideration the operation and support, speed and cost of construction. The service tunnel provided access between the running tunnels during normal and emergency situations and was equipped with a guided transport system. It was also where the water and pumping mains run and functioned as a fresh air supply duct to the tunnels in normal working condition. In addition, the service tunnel would function as a lead tunnel during construction which allowed the workers and engineers to assess and ascertain the uncharted ground conditions before advancing the main tunnels.

Basing on the existing geotechnical investigations, past tunneling expeditions and two additional geotechnical and geophysical surveys carried out by TML on the English Channel along the proposed tunnel line, it was ascertained that there was a distinct sub-unit of the Lower Chalk layer known as the Chalk Marl running continuously between the two terminals. Chalk

Marl, made up of alternating bands of marly chalk and limestone, was found to be the best tunneling medium as it was essentially impermeable (due to its high clay content) and provided good short term stability under excavation, thus minimizing the number of supports required (Figure 5). It was designed to be bored in the bottom 15m of the Chalk Marl layer to minimize the ingress of water from the fractures and joints, but above the Gault clay which is susceptible to swelling when wet, imposing high stresses on the tunnel lining. The chalk marl strata dipped gently at less than 5° with smaller displacements of less than 2m due to faulting towards the UK side; whereas the strata dipped severely towards the French side (up to 20°) with much larger displacements of up to 15m (Gueterbock, 1992). Chalk at the French side was also harder, more brittle and fractured. This thus led to the use of different tunneling methods on the English and French sides.

The seaward and landward bores for all three tunnels on the UK side began at Shakespeare Cliff. Construction traffic would enter the tunnel via a new inclined access (Adit A2) at the Lower Shakespeare site, while worker access was built via a shaft driven to the tunnel level from the Upper Shakespeare site (Gueterbock, 1992). Due to the fast construction time required and the relatively dry chalk marl at the UK side, it was assessed that the New Austrian Tunneling Method (NATM) was most suitable for the UK tunnels. One feature of the NATM was the interlinking of design, construction method, sequence and plant and the success of this method depended on the continuous integration of these elements by the tunneling engineers. Six TBMs were used to drive the UK tunnels spanning a total distance of 84km. The TBMs were operated on an open-face mode with a front excavating

section and a rear gripper unit which acted as a temporary anchor point when the cutting head drove forward at 1.5m increments (Anderson & Roskrow, 1994). Excavation of the tunnel and erection of the tunnel linings were carried out concurrently. Depending on ground conditions, the thickness of the linings ranged between 380mm and 500mm. Expanded concrete lining was used for the UK tunnels where the unbolted lining was expanded against the excavated ground. Pads on the back of the lining allowed the formation of an annulus to be filled with grout to prevent water ingress (Byrd, 1996). Each 1.5m lining ring was made up of eight precast concrete segments with a key segment. Cast iron lining segments were only used in poor ground conditions.

Over at the other side, the tunnel drives started at the shaft in Sangatte in France. Due to the highly fissured ground resulting in very wet conditions on the French side, a different type of TBM known as the Earth Pressure Balance Machine was used. The TBMs were designed to operate both in open and closed modes. Close mode is characterized by the sealing off of the machine from the spoil around it and the cutting head, thus keeping pressure on the dirt in front as it excavated and allowing the machine to work in the dry as the pressure in the machine was higher than the outside. The arrangement of seals on the TBM allowed it to withstand up to 10 atmospheric pressures. When the TBMs reached dryer and more favourable grounds, they could then switch to open mode. While precast sections were also used on the French side, the materials used were different owing to the different soil conditions: neoprene and grout sealed bolted linings made of cast-iron and high strength concrete (Anderson & Roskrow, 1994). The French tunnels were

made of six 1.4 to 1.6m wide segments plus a key segment. A total of 5 TBMs were employed on the French side, and the bores from the UK and France were to finally meet in the middle of the English Channel in the tunnel breakthrough phase.

The Channel Tunnel project was huge by any standard, with a number of key factors that could potentially impact the parties involved: bi-nationality, private funding (thereby effectively transferring most of the financial risks to the contractors), schedule and cost. To stay attractive to investors and banks alike, the project had to meet the following priorities: minimum risk of cost overrun, minimum operating cost and maximum traffic revenue. It was recognized, from the outset, that the main challenge of the project was to resolve the logistical support associated with large scale tunneling and the fast-track nature of this project. The management, finance and technical challenges related to this project would be explored in the subsequent paragraphs.

The first management problem encountered was the sourcing of the large number of manpower required for the construction of the Channel Tunnel. This was conducted against the backdrop of the booming construction industry where there was stiff competition for labour. As a result, TML scoured beyond France and UK for skilled labour including experienced engineers and tunnel miners. TML also set up a training scheme with Kent County Council and the Manpower Services Commission to prepare workers for the myriad of jobs available as the project progressed. The main constraint for sourcing talent was the high remuneration that accompanied them

The second management challenge was to find a solution to dispose the huge quantities of spoil that boring 150km of tunnels would produce. The problem at Sangatte was solved quite easily as there was a suitable land dump near the construction site and spoil disposal was done by converting the tunnel spoil into a 50% slurry and then pumping it to the Ford Pignon dam above the site 3km away. However, there was very little space at Shakespeare Cliff and there was no suitable land dump nearby. Despite the fact that backfill amounting to 3.6M cubic meters of British spoil would be required at the later stage of construction, there was still a remaining 1.8M cubic meters of spoil that had to be disposed. Eurotunnel eventually found a solution which was to use the spoil to provide a flat area of land at the foot of the Shakespeare Cliff which would be landscaped and used for recreational activities. When environmentalists raised strong objections, Eurotunnel argued that huge logistical and traffic problems would result if the spoil were to be transported elsewhere. In addition, the spoil would be contained behind an expensive seawall of sheet piles and concrete designed to prevent the chalk fines from leaching into the sea. The constructed seawall, spanning 1795m long and up to 11.36m thick, was designed as a short term breakwater and a long term retaining structure. This land (made of spoil) was subsequently transformed into the Samphire Hoe Country Park. Another aspect of concern was the delivery of materials to the site. Whenever practicable, delivery was done mostly by rail (for speed and convenience) and the materials delivered include the precast concrete linings, sheet piles and aggregates.

Next, another management challenge was the method of obtaining the large volume of concrete required. 442, 755 concrete segments of the highest quality mixed from strong, un-reactive materials in 35 different sizes were required. They were designed to last 120 years subjected to loadings in the worst case scenarios under two separate limit states and had to resist seismic activities, be watertight and to maintain its structural integrity regardless of the loading type (Byrd, 1996). As it was apparent that no precast company could supply such segments to fulfill TML's requirements, TML had to create its own precast yard at the Isle of Grain in Kent, producing segments of the strongest concrete.

In addition, the decision to drive all the UK tunnels from a single worksite gave rise to complex logistics problems because it had to support five TBMs at any one time. They required 1000 precast concrete segments daily, together with other materials such as track, cables, pipes and vent ducts. Also, at least 18000m³ of excavated spoil had to be removed daily. This challenge was solved by the process of separation: personnel would enter the tunnel via the 110m deep shaft; spoil removed through Adit A1 on a 2400T/hr capacity conveyor and other materials transported on the five-line railway in Adit A2.

Moreover, the three 50km-long tunnels had to be made an operational railway through the installation of catenary systems, cooling pipes, drainage, tracks among many others. Given the myriad of systems that had to be installed (e. g. 550km of drainage, fire and cooling system pipes, 1330km of cable fitted on the cable trays), TML had to manage more than 40 subcontractors competing for space on the tunnel delivery trains. The right

equipment had to be supplied to the exact location at the right time; especially when the delivery trains take more than an hour to negotiate the deep ends of the tunnels and a missing item would have caused delay to the works. TML resolved this issue by running the tunnel works akin to a production line – a materials controller was employed from the motor industry to ensure smooth work processes and led the coordination and planning efforts (Anderson & Roskrow, 1993). Also, TML constructed 4 diagonal cross tunnels connecting the three main tunnels to allow the delivery trains to switch between the three during the services installation phase, thereby alleviating the difficulty of moving the materials and spoil to and fro the tunnel.

Sourcing finances for the mega project was also one of the management challenges faced. Given that the initial estimation of the project cost to be around 5 billion pounds, a large amount of money was required to see the project through to completion. As the project had to be privately funded, Eurotunnel had to source beyond the national boundaries to secure investments. They therefore devised a financing scheme to help them tide the crisis: the scheme would provide for the cost of the tunnel to be financed by £5 billion worth of bank loans, with additional £1 billion equity from the owner, institutional investors and public offering. Preliminary equity financing would be raised in two stages (known as Equity 1 and Equity 2). Equity 1 worth £47 million was raised by cash placement by the founding shareholders. Equity 2, worth £206 million, came from both British and French investment institutions. They later came up with Equity 3, worth £770 million, and raised it by way of public share offering through the Paris and

London stock exchanges concurrently. The Channel Tunnel project was thus able to proceed.

Perhaps one of the greatest management challenges was how to enable the French and British work closely together. Separated by 34km of sea, their cultures are very different. Moreover, the building codes and training (and thus the limit states of design) were different. It was a challenge bringing two different engineering styles together. To overcome this challenge, it was decided that both countries use their own design codes for their part of the channel. Gordon Crighton, a Scot, was brought in to lead the engineering team so that both the British and French would not have disagreements since both countries had good relations with Scotland. This enabled the engineering team to work cohesively together. When it came to the design parameters, both the French and the British had to compromise. For instance, the English wanted the service bore to be 4.5m in diameter, but the French wanted 5m. In the end they agreed to a diameter of 4.8m.

Besides the need to overcome the challenges faced in project management, a number of technical challenges also had to be overcome. Firstly, keeping the machines on course was one of the most complicated technical challenges faced. While most tunnel miners use a high-tech satellite mapping system to chart the tunnel route, this system was not effective for the Channel Tunnel as it was too far underwater. Excellent and exact mapping was essential for if the British and French tunnels were to be misaligned even by a small margin, they would not be able to meet up as planned in the middle of the English Channel. Therefore, the engineers developed a high-tech laser guidance system. A red laser on the cutting

head of the TBM would send a beam forward; hitting a control point which would relay the information to the computers onboard the service trains located behind the cutting head to help them stay on course. This system enabled both teams of TBMs to successfully stay on the intended course and meet each other in the tunnel breakthrough.

Another technical challenge was that the locomotives that were used to pull the tunnel lining segments and spoil trains broke down frequently under wet conditions. Under such conditions, the wheels of the locomotives lost traction and span on the slopes; and their electric systems were laden with salt moisture and often leading to malfunction and power failure (Byrd, 1996). Even though the locomotives were designed to be powered by a 500V DC overhead supply and the batteries were supposed to be recharged while moving in the underground development, they did not charge up due to the presence of water. This challenge was overcome by redesigning the locos. The loco's weight was increased for better traction and much larger capacity batteries were installed. Improvements to the pantographs design were made. The increase in efficiency and lesser loco breakdowns made up for the corresponding increase in costs.

Another technical challenge arose when the tunnels emerged from the underground tunnels up to the surface approximately 900 meters short of the terminals at the UK side. This was resolved where engineers employed three different tunneling methods to complete the tunnels via the difficult gault clay at Castle Hill. First, the NATM took the tunnel through the geologically challenging strata at Castle Hill; while at either side of the hill, cut-and-cover construction and top-down construction were used. Cut-and-

cover work involved excavating the area and building the tunnel using RC boxes. Top-down construction (usually used in tight spaces) involved building the roof of the tunnel first before excavating the ground below it. The use of 3 different methods of tunneling within a short 900m stretch reflected the excellent engineering concepts used in this project.

Fourth, following the geophysical and geotechnical surveys, the British anticipated that the soil stratum was mostly dry. They thus configured the TBM in open mode. However, they tunneled into unexpected micro-fissured chalk which was very permeable and very quickly incapacitated the TBM. Dry chalk started to give way to moist chalk and chunks of rocks started to fall from the crown and sides of the newly excavated bore (Andrew & Roskrow, 1994). The circle was not sufficiently accurate from which the concrete lining could expand. Work was then stopped to ensure worker safety. Eventually, the TBM was modified in situ. A series of trailing fingers were installed behind the cutting head and spanned across the lap between the head and the last section of the lining (Gueterbock, 1992). These fingers, when sliding forward during boring, restrained the chalk while at the same time allowed the segments to be erected and grouted quickly. TML also applied extensive waterproofing to the machinery and hoses to prevent them from further saltwater attack. Hence, the TBM started to make better progress and the delay was minimized.

Other technical challenges and innovations include the removal of the TBMs that have completed the service tunnel. Stuck in the middle of the tunnel and under the sea, these TBMs were not able to move back up. While they could have been taken apart and removed piece-wise from the tunnel, it was

undesired as this would incur high costs. This challenge was overcome by driving one of the TBMs slightly off the course of the tunnel and burying it into the chalk rock. This way, the other opposing TBM could drive forward out of the tunnel. The British TBM was the one chosen to drive off-course and buried. After it drove into the rock, it was sealed off and the tunnel wall was covered with concrete slab. The French TBM was thus able to move forward to the other side of the coast and be removed. This construction innovation enabled the contractor to save costs.

For a project of this gigantic scale there was bound to be budget overrun and delays. The project entailed designing; building and commissioning the entire project in just seven years and be ready for opening in May 1993. This was not to be, as at the end of the project, the estimated budget overrun was 80% (total project cost reaching £9.2 billion) and the official opening of the Channel Tunnel was May 1994, one year later than the contractual completion date.

One cause of the delay was due to the passing of the Parliamentary Bill which was required for the commencement of the works. This was due to the objecting voices towards the building of the Channel Tunnel and the Bill could not be passed quickly enough. The delay took up most of the float that TML initially had and any further delay could severely impede the construction schedule. To overcome this difficulty, TML started preliminary site works like constructing the precast yard at the Isle of Grain and placing orders for the materials even before the Parliamentary Bill was passed. It also started a global search for manpower and engineering talents.

Another cause of delay during the early days of construction on the French part was due to the financial collapse of one of the firms involved in building the TBM. However, the delay was reduced with the quick mobilization of the TBM at the huge Sangatte shaft which allowed the 400T TBM body to be lowered in one piece into the tunnel. On the British side, it was the unexpected wet ground conditions that caused the slowdown in tunneling works and resulted in a delay of more than 3 months. However, the engineers modified the TBMS by installing the trailing fingers behind the cutting head. Very soon the TBMs started to drive at record speeds.

Third, the major cause of schedule delay was the dispute between TML and Eurotunnel. The contractor's claim that Eurotunnel owed it £1.45 billion for the M&E systems installed in the tunnel was the main cause of dispute. This figure was more than twice the figure stated in the Contract, which Eurotunnel insisted that the sum owed was less than £900 million (Byrd, 1996). The protracted legal battle between the two entities delayed the project. TML decided to finance its own works while Eurotunnel sourced for funds, which potentially would push the project completion date further back. In the end, Eurotunnel struck a deal with TML where TML would need to hit a series of milestones over the months in 1993 to handover the project to Eurotunnel by Dec 1993. In return, Eurotunnel would give an advance payment of £235million to TML so that the latter would not run out of funds. This incentive enabled TML to push for progress and minimize delay.

There were few causes of budget overruns. Firstly, the original start to completion duration was a mere 7 years, meaning that the project had to move from design development to completion in that length of time. As a

result, many design problems (e. g. open mode TBMs used by the British) were not identified and resolved at the start of the project and no provisions were made for these provisions in the initial cost estimates. Eurotunnel thus had to source for additional funds for the project.

Secondly, due to the competitive nature of the project, CTG/FM had to cut their cost estimates to the bare minimum in order to make a successful bid. This was made with the knowledge that the competing consortia would be evaluated on financial standing – thus the rationale for lowering the profit margins. The subsequent cost increase was blamed on delays from the parliamentary process and early financing problems.

Thirdly, the budget overrun was caused by the increase in costs and number of materials required for the project. Even though TML had planned to line the tunnel with cast iron segments rather than concrete in wet ground as they were more watertight, they had not expected the UK TBMs to also hit poor ground (contrary to geotechnical analysis results). The required amount of cast iron had already exceeded the total amount of cast iron originally estimated when this happened and cost increase was inevitable. TML tried to reduce costs by hastening the tunneling process and modifying the TBMs.

While the project was delayed many times due to boardroom disputes and unexpected site conditions, innovative ideas were put into practice that helped to increase productivity. For instance, due to the poor ground conditions and water ingress at the UK side, TML had wanted to use cast-iron linings which at that time were already over-budgeted. However, innovative ideas led to the modification of the tunnel linings, known as hybrid linings

where areas of high stresses would be taken by the iron while the bulk of the lining ring was still made of concrete. Not only did these linings save TML close to £20million, it also reduced three months on the critical path. In addition, improvements and modifications to the TBMs were made, their lining erectors and spoil removal systems extensively changed, their electronic systems simplified and waterproofed. The TBMs' performance improved tremendously and soon they were breaking world records for tunneling rates. Miners and workers were also incentivized for good work progress so that their morale remained high. Their pay was reviewed to remain market- competitive. Eurotunnel also formed a policing arm known as the Project Implementation Division to keep check on the construction progress and on TML to do more to stay on the scheduled timetable.

The total death toll for this project was increasing at an alarming rate towards 1990. Safety at the construction sites were put under intense scrutiny. This prompted TML to embrace DuPont's safety practices and principles, and made a few innovations to its safety plan. Firstly, a series of mainly one-to-one audits were carried out by the foremen and supervisors on the workers at work. These were no-risk audits, and the auditee was encouraged to tell the auditor of his observed actions that were less safe than desired and was also encouraged to make safety suggestions.

Completed audits identifying the auditor (but not the auditee) were analyzed by a senior line manager and summarized for the local line manager to identify trends and plan follow up actions (Byrd, 1996). As a result, many previously unidentified safety issues were found and subsequently resolved or mitigated. Secondly, safety prizes were awarded, through lottery, to

individuals or team of personnel who managed to achieve 25000 of accident-free work activity. Thirdly, poster campaigns were carried out to address safety issues such as track safety and proper PPE. These campaigns were complemented by other form of media such as safety notes in payslips, on site video presentations and toolbox briefings to all employees. These safety practices resulted in zero deaths for the next two years of construction.

To conclude, the Channel Tunnel was a mammoth privately-funded project in its own right. It was of no mean feat for the completion of a project involving 2 countries separated by a sea 34km long and both being traditionally rivals. Even though it was completed a year late and at least cost overrun of at least 80%, the Channel Tunnel can still be considered a success, this in view of the management, technical and financing challenges faced by the parties throughout the project. Apart from the famous senior management battles and arbitration between the owner and contractor, it must be noted that the management and technical innovations led to an increase in productivity and should be used as a reference for future projects.