The detailed design of the Medway Tunnel project

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Immersed tube tunnels may be considered to be particularly suited to a design-and-construct form of contract, in that there is considerable influence on the permanent structure by the temporary works required for the float-out and immersion of the tunnel elements. The scope of the reference design produced by the engineer for the Medway Tunnel project, which allowed tenders to be sought, afforded flexibility for the tenderers in their options for constructing the immersed tunnel, the cut-and-cover tunnels, and their approaches. This paper discusses the designs carried out by Mott MacDonald for the various forms of construction employed on the project by the contractor. These works include the cut-and-cover tunnels which were constructed using permanent diaphragm walls or with cast-in-place concrete within a temporary combi-pile wall arrangement, the piled slabs and gravity structures which were employed on the open approaches, the innovative sand-placing method used for the embankment built on very soft ground, and the immersed tunnel itself. The paper also addresses the coordination required in the design-and-construct process between the designer and contractor, and also between the civil and mechanical and electrical works. Finally, the paper discusses some of the technical complications encountered during the construction of the project, and how the design-and-construct form of contract was beneficial in achieving a rapid and satisfactory solution.

Keywords: concrete structures; design methods & aids; tunnels & tunnelling

Introduction

Mott MacDonald was commissioned by the Medway Joint Venture, a contractor grouping of Tarmac Construction of the UK and HBM of the Netherlands, to act as their designer for the tender submission for the Medway Tunnel project. Symonds Travers Morgan, in association with Rendel Palmer and Tritton, had been previously appointed as engineer by Kent County Council for the project. The engineer had produced an outline scheme for an immersed tube tunnel crossing of the River Medway, which would be built under a design-and-construct contract. The tender documentation was issued to contractors in July 1991.

2. Mott MacDonald's role as designer was to develop the concepts prepared by the engineer which effectively defined the employer's requirements for the project. The design responsibilities included all aspects of the civil and structural works plus the mechanical and electrical engineering. Assistance was provided to Mott MacDonald by TEC of Holland. Close liaison was also required with the design arms of the contractors' organizations—TCES of Tarmac and Delta Marine of HBM—who developed the temporary works for the tender design (see Fig. 1).

3. Various concepts and proposals were addressed by the design team during the five-month tender period. The tender submission was returned on 21 December 1991, and included two comprehensive designs—for a scheme which fully complied with the employer's requirements, plus an alternative scheme which offered several innovative solutions which are discussed further in the following section.

4. Lengthy discussions were held between Kent County Council and Medway Joint Venture regarding the technical viability of the options proposed in the alternative scheme, and in July 1992 the Joint Venture was awarded the design-and-construct contract for the project. Mott MacDonald was subsequently appointed as named designer, responsible for all aspects of the permanent works.

Tender design

5. The overall project involved the design and construction of approximately 1500 m of twin dual carriageway highway, extending from Anthony's Way in Strood, on the west side of the River Medway, through to Pembroke Road interchange adjacent to the Chatham Maritime Development and the Historic Dockyard areas on the east (Fig. 2). The alignment of the new highway would rise from the new Anthony's Way roundabout to cross the soft ground of the tidal Whitewall Creek, before descending into cutting and tunnel with a maximum gradient of 5%. On the east bank the road rises at a gradient of 5% to connect with the future Gillingham Northern bypass route commencing at Pembroke Road. Central to the

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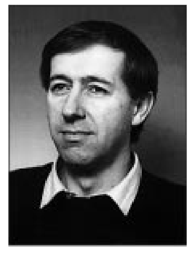

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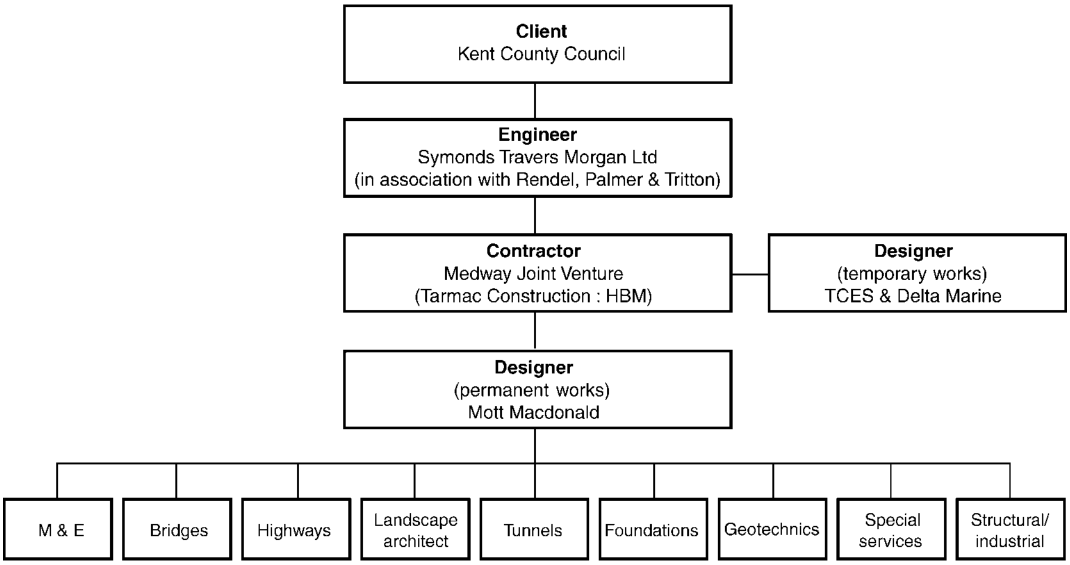

Fig. 1. Design organization chart

project would be the tunnel across the river which is approximately 350 m wide at the location of the crossing.

6. The options presented to tenderers included two locations for the eastern tunnel portal, the portal for the long tunnel option being some 140 m further eastwards, away from the river, thus allowing more usable land area above the completed works. The respective tunnel lengths were 580 m and 720 m for the two schemes. In neither case did the engineer dictate, in his outline design, the extent of the immersed tunnel section for the crossing, or the forms of construction for the cut-and-cover works. No instructions were given in the tender documents as to where a casting basin for the construction of the immersed tunnel elements could be located. The cross-section for the tunnel presented in the outline scheme defined the employer's requirements for the carriage-ways, the emergency walkways, and the traffic envelope, showing space above the traffic envelope throughout the length of the tunnel for the necessary lighting, signage and ventilation fans.

7. The tender designs prepared by the Medway Joint Venture grouping determined that three tunnel elements would be required for the crossing, each approximately 120 m long. These elements would be constructed in a casting basin located on the east bank of the river; two of the elements would be on the final alignment of the crossing, in the area which would be occupied by the eastern cut-and-cover tunnel and approach structures, with the third element alongside and to the south of the completed works. The tender designs showed the casting basin to be formed within vertical retaining walls, mainly diaphragm walls, to minimize land take. The schemes submitted with the tender included a bid which was fully compliant with the engineer's proposals, with ventilation fans at regular intervals along the length of the tunnel.

8. Fundamental to the alternative proposal was the innovative concept of providing banks of jet fans which were located near to the tunnel portals, in raised niches within the roof slab of the cut-and-cover structures (see Fig. 3). This alternative allowed the overall depth of the tunnel section to be reduced over the majority of its length, thus providing a more cost-effective solution. The employer's requirements defined the profile of the roof of the tunnel with regard to its position below the river bed. Thus the reduction of the depth of the tunnel section

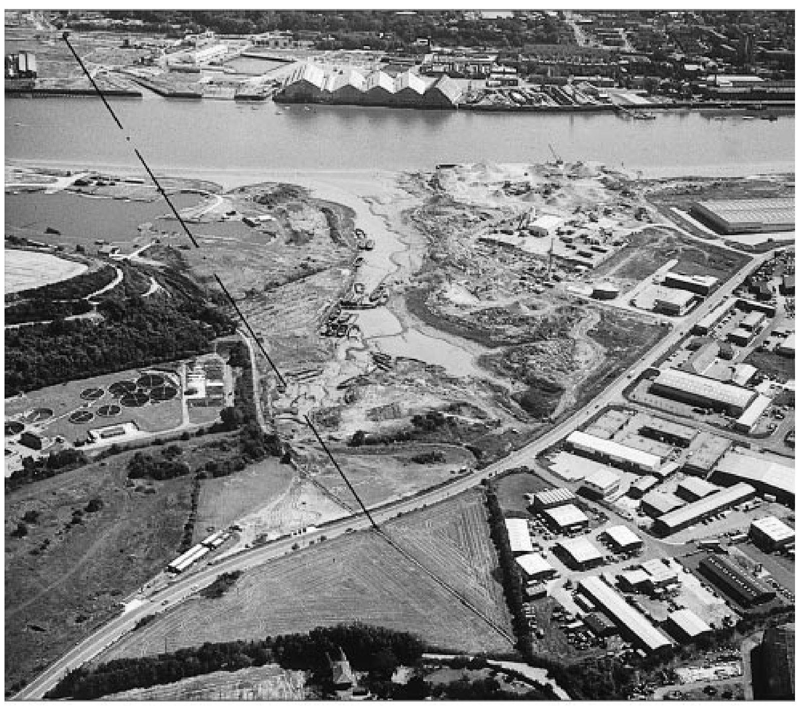

Fig. 2. Aerial view of site prior to start of construction

effectively raised the tunnel invert, thereby reducing the depths of dredging within the river and the amount of excavation at the landfall structures, providing all-round benefits.

9. The other major departure from the employer's requirements in the alternative offer was the deletion of the external waterproof membrane around the immersed tube section. The only previous immersed tube constructed in the UK was protected by steel plate under the base slab and on the outer walls, and a bitumen membrane on the roof slab. The Medway Joint Venture's proposal was to provide a means of designing and constructing durable concrete which itself would act as an effective waterproof barrier, a concept which had been used successfully on other concrete immersed tubes constructed by one of the partners of the joint venture.

10. The alternative ventilation concept was adopted by the client from the outset of the contract. After more in-depth consideration, the proposal to delete the external waterproofing was also accepted.

Design procedures

11. The contract documents required the contractor to take full responsibility for the design of the project, and to this end a system of self-certification was employed. However, the designs were still subject to the approval of the engineer and were to be carried out in accordance with the various codes and standards stated in the employer's requirements.

12. Before detailed design could commence, technical approval in principle (TAP) had to be sought from the engineer. The TAP documents prepared by the designer defined how the design would be carried out and listed, among other things, the relevant design standards that would be employed, geotechnical data and parameters, loadings, methods, and any computer programs that would be used in the analysis. Because of the varied and complex nature of the overall project, individual TAP submissions were made which related to particular aspects of the works. Subsequent to the acceptance of TAP, the detailed design and construction drawings were similarly issued to the engineer for approval. Finally, design and independent check certificates were submitted by the designer on completion of the detailed design.

13. For the successful implementation of the design and construct contract, close liaison was required throughout the duration of the project between Mott MacDonald, the Medway Joint Venture site staff, and the temporary works teams. The designs needed to suit the construction methods and, more importantly, needed to respond to the construction programme which the contractor was proposing for the works.

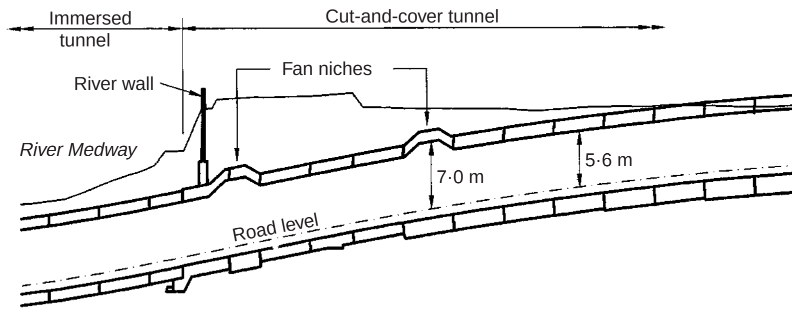

Fig. 3. Longitudinal section through cut-and-cover tunnel showing niches in roof for ventilation fans

Conversely, the construction staff needed fully to understand the design procedures. The interfacing during the initial months was intense. Ultimately, this proved to be vital to the overall understanding and hence the success of the project.

Western approach

14. The new roundabout at Anthony's Way marks the start of the project at the western end of the site. From this point the new highway follows a straight alignment through to the end of the project at Pembroke Road (Fig. 4). For flood protection on the west bank, the project required the new roadway to attain an elevation of 7·2 m above datum. This necessitated the construction of a 6 m high embankment across Whitewall Creek, an area of very soft ground subject to tidal flow.

15. East of Whitewall Creek the new roadway enters cutting, and descends at a maximum gradient of 5%. A flood bund runs parallel to the highway from the high point and across the tunnel portal. At the river itself the finished roadway is at an elevation of $-9{\cdot}2$ m which is in excess of 12 m below the mean high water level. The design of the western approach was based on extensive numerical modelling of ground settlement and stability which was supported by the geotechnical investigations.

Whitewall Creek

16. The embankment over Whitewall Creek and the adjacent low-lying land extends for a length of approximately 300 m. Almost the full length of this embankment was constructed over soft clay and clay fill which would be subject to settlement. The embankment design required the use of wick drains through the soft clay to ensure that most of the primary consolidation occurred before the road pavement was constructed (see Fig. 5). Programme restrictions meant that hydraulically placed fill would be the most appropriate solution for the embankment construction to allow this consolidation to occur.

17. The construction sequence first required placing of a bund of crushed rock over geotextile fabric which would act as both a filter and a reinforcement during the early part of the

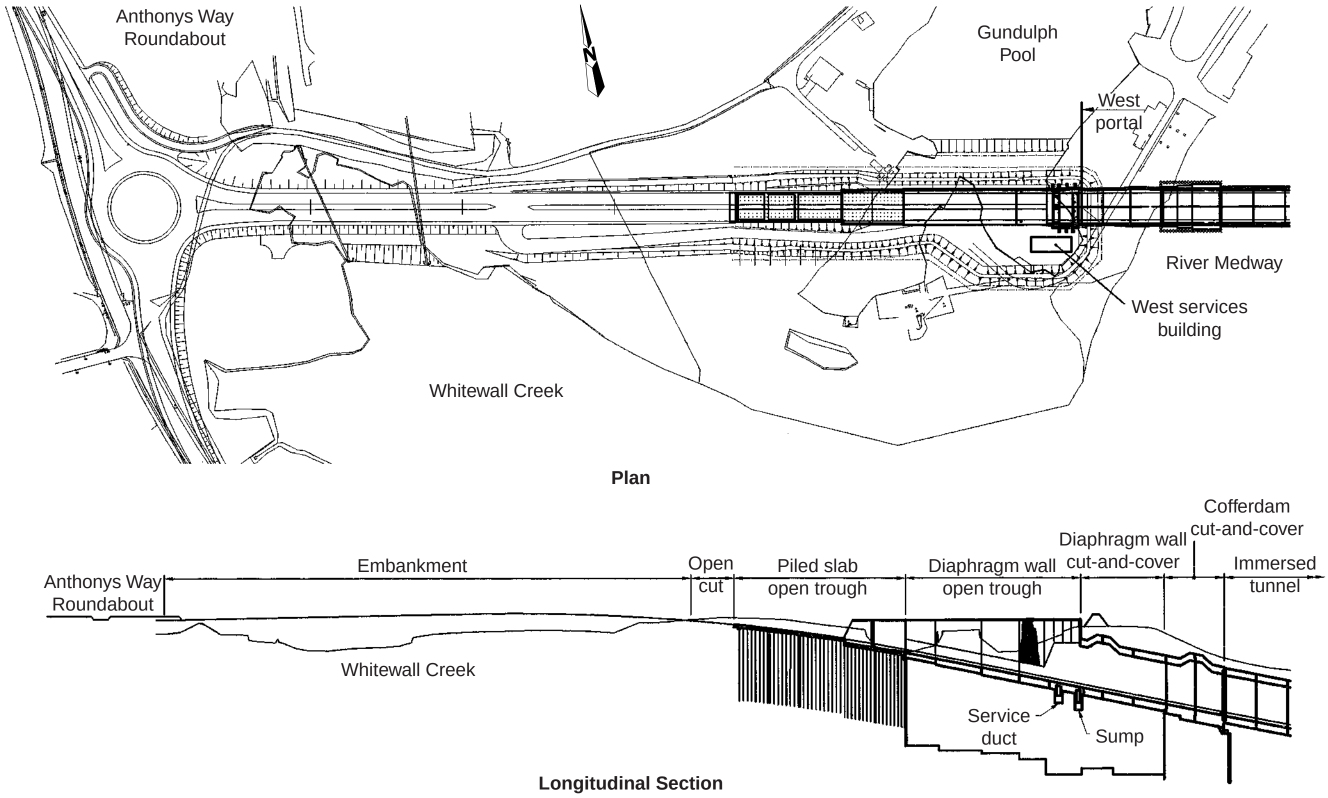

Fig. 4. Plan and profile of western approach

primary consolidation of the underlying soft clay. The hydraulic fill was then placed in layers to a level where it could be dozed to provide a working surface for the installation of the wick drains. The placement of the final bulk fill was only possible after the wick drains had been in place for ten months, which was the estimated period for 70% of the primary consolidation to occur.

18. The increase in strength in the soft clay that results from the dissipation of pore pressure due to consolidation was required before the completion of the embankment. The top level of fill was controlled by the consideration of embankment stability, which allowed a thickness of surcharge fill of up to 1 m above the finished pavement level. This fill was left in place for approximately 15 months, which was the estimated period to allow 90% of the primary consolidation to occur. After the excess fill was removed to the level of the underside of the pavement, and the pavement constructed, the degree of pore pressure dissipation corresponded to almost complete primary consolidation.

19. The principle of the design was that the compacted upper part of the embankment was thick enough to ensure that the effects of live load did not cause sufficient shear stress in the uncompacted lower part which would result in plastic deformation. Previous experience with this construction technique was that the long-term settlements of the hydraulic fill were not significant. It was considered that at the Whitewall Creek site the settlement of the underlying soft clay would be the dominant factor in the overall settlement of the embankment.

20. The numerical analysis of the embankment presented some complexity because of its staged construction with berms and wick drains, and because of the varying thickness and properties of the underlying soft clay. The basic analysis for settlement used one-dimensional consolidation theory at several positions along the embankment to develop the longitudinal variation of settlement and to provide

Fig. 5. Embankment construction showing wick drains and placement of hydraulic fill

an assessment of the time for settlement to take place.

21. The primary analysis for slope stability was carried out using slip circle and non-circular analysis computer programs. In critical areas a more rigorous two-dimensional analysis was carried out using a finite element program, which provided a full section analysis of the stress distribution, the primary consolidation, the effect of the wick drains and plastic yielding. The analysis also checked on the stability of the embankment and modelled the staged construction as an implicit part of its analysis procedure.

22. The results of the analyses predicted that the final settlement of the soft clay at the centreline of the carriageway would attain a maximum value of 1·1 m, and under the bund would be 0·7 m. The actual settlements that occurred in the Whitewall Creek area indicate that these figures were slightly exceeded, although it is thought that the dewatering activities which were taking place concurrently elsewhere on the project may have contributed to the additional consolidation.

Piled slab

23. At the eastern end of the embankment the road enters cutting through soft alluvial strata. This required partial excavation and replacement with a capping layer to provide a foundation of adequate stability. As the depth of the cutting increases, the road foundation comes nearer to the soft clay which itself becomes thicker. The stability analyses determined that an alternative founding solution should be provided, and a piled slab was designed to support the roadway over the soft clay. The overall length of the piled structure is 110 m.

24. The primary purpose of adopting a piled slab structure was to achieve a stable pavement by founding the piles in the silty sand and gravels that underly the soft clay. A secondary function was to stitch the soft layers together. Groundwater seepage in any sandy layers within the clay would have the effect of transmitting groundwater pressure into the clay which could otherwise cause hydraulic heave of the foundation. The slab was constructed on a layer of granular fill, wrapped in geotextile, which provided a working platform for the construction of the slab, and ensures free drainage of groundwater into fin drains located at each side of the slab. The fin drainage connects to carrier drains which follow the level of the underside of the slab. Accordingly, there can be no uplift force on the piles as the slab is surrounded by drainage media which can readily overflow to surface level, and be accommodated by the surface drainage regime, should the carrier drain become blocked. Thus the piles were designed to support the weight of the slab, pavement and live load only: no uplift capacity was required. The subsoil drainage system was designed to control the stormwater fed seepage to minimize infiltration into the soil, and to lead runoff into the sump at the tunnel portal.

25. As the alignment descends, the volume of groundwater seepage increases and vertical retaining walls are necessary on each side of the piled slab. At this greater depth weep holes were provided through the slab and the vertical walls of the structure, draining into the stormwater system. This prevents any perched water table, which may occur within the granular fill surround, from exceeding a level of +2 m above datum.

Open approach with diaphragm walls

26. At a position approximately 150 m from the west bank of the Medway, the route crosses Gundulph Pool, a Ministry of Defence diver training facility. The contract required that the southern part of Gundulph Pool be backfilled to facilitate the new highway. The remainder of the pool was preserved for diver training. The soils underlying the pool area comprised soft clays, and the Joint Venture considered that the most appropriate form of construction in this area would be diaphragm walling. For economical construction, the length of diaphragm walling needed to be maximized. Diaphragm walls were employed over a 170 m length of the western approach structures, the first 115 m being open trough construction, followed by 55 m of cut-and-cover tunnel using the same technique (see Fig. 6).

27. The design for the open trough section incorporated a reinforced concrete slab for the roadway foundation, with full moment connection to the retaining diaphragm walls on either side. In the permanent case the 800–1000 mm thick diaphragm walls act as cantilevers supported by the base slab. The walls are clad with brickwork on a concrete rubbing strip. The void between the brickwork cladding and the diaphragm wall accommodates a half-pipe drain which leads to the sump at the west tunnel portal. A two-dimensional plane frame method was used as the primary form of analysis for all the structures on the western approach.

28. The length of open approach immediately outside the western tunnel portal accommodates a major services duct and drainage sump. The design concept was similar to the previous length of structure but the diaphragm walls consisted of T-shaped sections which form a 9–10 m high cantilever wall.

Cut-and-cover tunnel

29. Although the portal position was fixed by the employer's requirements, the actual length of the western cut-and-cover tunnel was dictated largely by construction considerations.

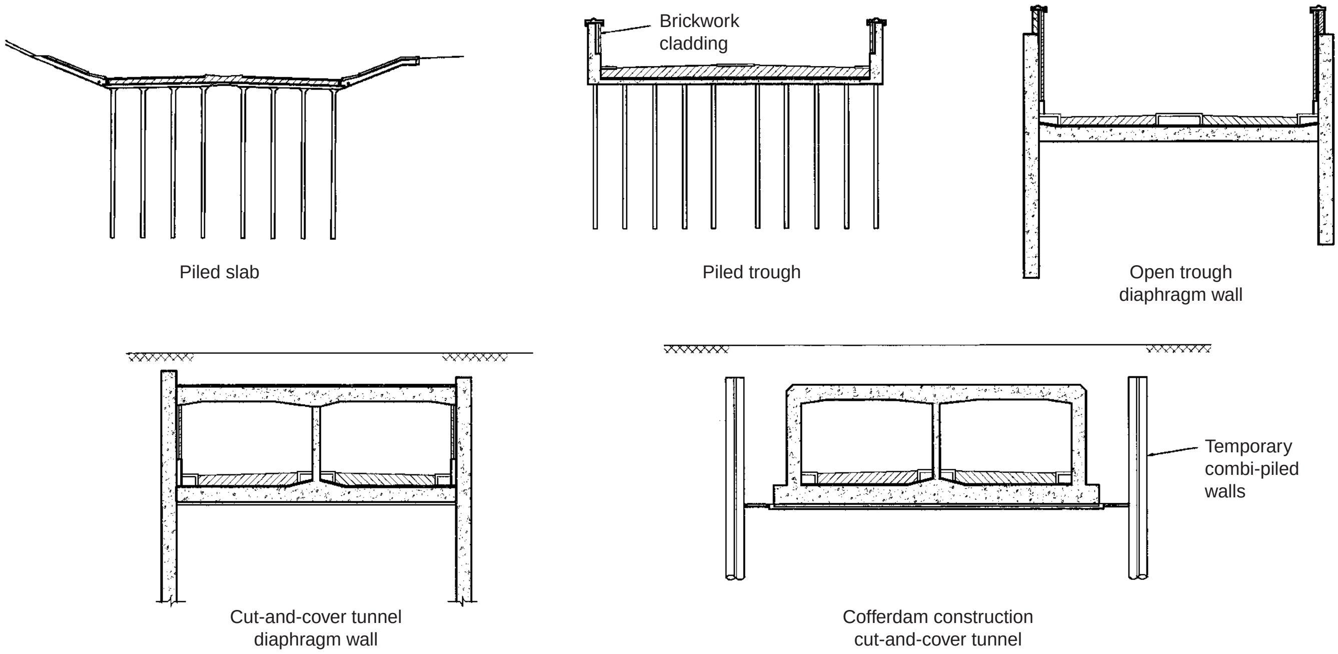

Fig. 6. Cross-section of structures employed on western approach

The river end of the cut-and-cover section would interface with the immersed tunnel and the Joint Venture considered that for safety during the immersion operations the roof of the immersed tube should always be below the mean low water level. This fixed the interface location and hence the length of tunnel that could then be constructed by cut-and-cover techniques at 95 m.

30. The amount of tunnel that could be constructed utilizing diaphragm walling, already employed on the open approaches, was maximized but was limited to the land above mean high water level. A 55 m length of cut-and-cover tunnel was constructed bottom-up using temporary propping. The base slab spans between the outer diaphragm walls acting as a permanent prop. This slab was designed with full moment connection to the walls, as was the roof slab which spans between the outer walls and the central wall of the tunnel. Waterproofing for this length of walled tunnel was provided by membranes on the roof and base slabs; seepage through the diaphragm walling was collected within a drainage channel located in the void between the wall and the brickwork cladding which formed the finished surface, similar to the approaches.

31. The remaining 40 m of tunnel in the inter-tidal zone was required to be built within a temporary cofferdam. This length of tunnel was designed to be watertight without the use of a waterproof membrane, using similar technology to that employed on the immersed tube structure. Longitudinally, the tunnel was constructed as two discrete units, each 20 m long, with articulation joints between the units. This is also similar to the immersed tube and is explained further in that section of this paper.

Immersed tube

General principles

32. The basic principles of immersed tube construction are outlined as follows. The tunnel elements are constructed in the dry, in a purpose-built casting basin. Once the elements are completed, the ends are sealed with watertight bulkheads. Cast-in prestressing cables are employed, running the length of the element, to make the structure act monolithically during the immersion operations. Internal water ballast tanks are used to control the buoyancy of the element. The casting basin is then flooded and the elements are individually floated and prepared for towing and immersion in a trench which has been dredged in the river bed.

33. When the elements are in position above the trench they are ballasted with water and lowered onto temporary supports placed on the bottom of the excavation. The elements are placed, firstly, against an *in situ* length of cut-and-cover tunnel, also made watertight by a temporary bulkhead, and subsequently against the preceding immersed tube element.

34. Jointing under water is made possible by specially-made rubber gaskets, known as Gina gaskets, and by utilizing the hydrostatic pressure which acts on the structure (see Fig. 7). When the gasket on the leading end of the first tunnel element meets with the *in situ* section, a small cavity exists between the two bulkheads. As the water trapped between the bulkheads is pumped from the cavity, the

lowered immersed tube element is pressed against the *in situ* structure by hydrostatic pressure on its free end. Thus the gasket is compressed to form a watertight seal. This primary seal is sufficient to allow the bulkheads to be removed, although a secondary permanent seal is later installed. Subsequent elements are positioned in the same way. A sand foundation is then placed under the element, the trench backfilled and the tunnel completed.

35. For the Medway Tunnel, it was determined that three tunnel elements would be required for the crossing, and that these would be constructed in a casting basin facility located partly on the line of the crossing, on the east bank of the river. During the intense liaison between the design and construction teams in the early phases of the detailed design period, minor adjustments were made to the precise lengths of the individual units that made up each of the tunnel elements. This ensured the compatibility of the permanent works with the most cost-effective construction. The deliberations determined that tunnel elements (TE) 1 and 2, which were to be constructed on the line of the tunnel, would each be 126 m long, and TE3, which would be built alongside the other two elements, would be 118 m long (see Fig. 8).

Buoyancy considerations

36. In order for an immersed tube tunnel to be constructed efficiently, it must possess sufficient buoyancy to be able to float during the construction stage, yet with the addition of the minimum amount of permanent ballast should possess an adequate factor of safety against uplift for its design life. The shape and size of the cross-section are fundamental to the buoyancy considerations. The cross-section of the Medway Tunnel is a straightforward twin-cell reinforced concrete structure (see Fig. 9). Each cell is required to accommodate two lanes of traffic and emergency walkways, the width of which were defined in the employer's requirements. The adoption of the tender design concept meant that the ceiling space above the traffic envelope need only be sufficient for lighting and lane closure signs, the ventilation fans being located in the cut-and-cover tunnels.

37. Ideally, during construction the tunnel should be able to float with a nominal freeboard. The employer's requirements stated that the long-term factor of safety against uplift should be not less than 1·1. The permanent ballast, to provide this factor of safety, is provided by the weight of the road base material within the tunnel, and the weight of backfill on the structure, including a 1 m thick layer of rock protection. To increase the volume of backfill, extension toes were made to the tunnel base slab, which allowed an extra 1 m wide column of material alongside the outer

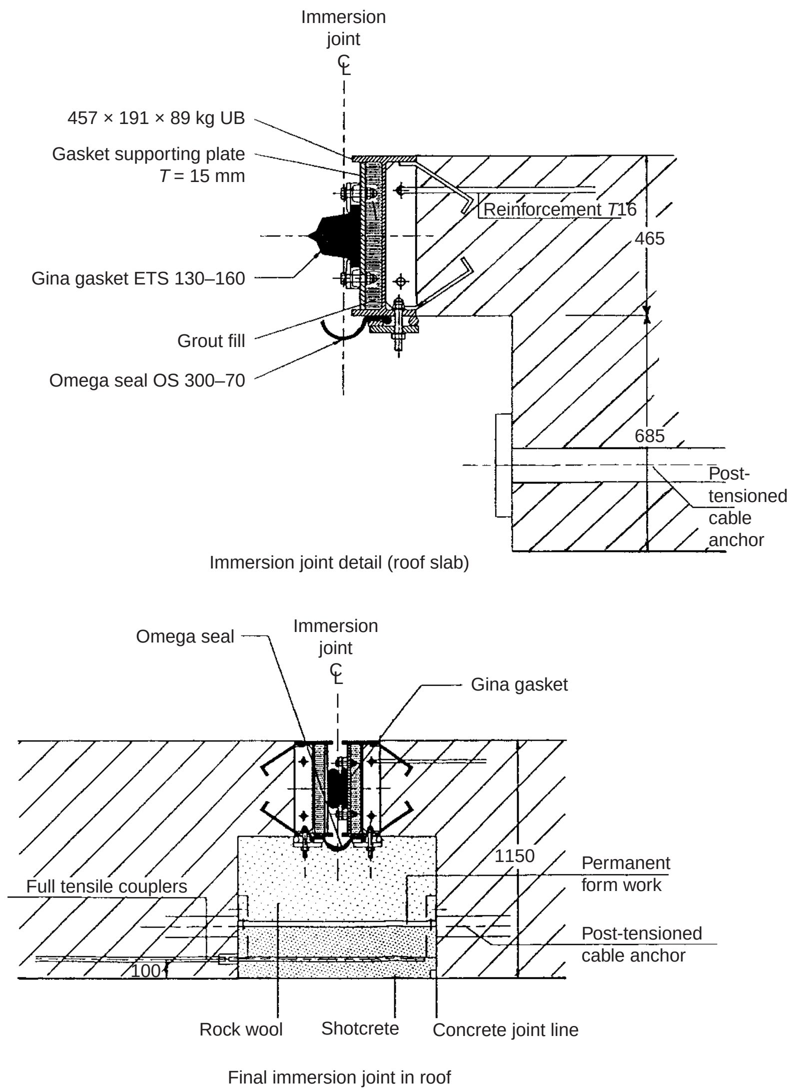

Fig. 7. Underwater jointing of immersed tunnels (dimensions in mm)

Fig. 8. Immersed tunnel elements in partially flooded casting basin

walls of the section to be included in the buoyancy considerations.

38. The basic cross-section had been established during the tender period, but minor adjustments were necessary during the early stages of detailed design because of commercial considerations. The Joint Venture pursued several options for their aggregate sources for the concrete to be used for the tunnel. The various aggregates differed in weight which, in turn, affected the concrete densities of the trial mixes. The variation in density was sufficient to affect the buoyancy calculations for the immersed tunnel. When the aggregate source was confirmed, large-scale concrete cubes were cast to determine the weight range which should be used by the designers in the final buoyancy calculations. 'Fine tuning' of the thicknesses of the outer walls and roof slab was required to achieve the final cross-section.

39. The overall buoyancy was further complicated by an excess pore water pressure which occurs within the chalk stratum upon which the immersed tube would be founded. The pore pressure relates to the tidal cycle of the groundwater level, but has a muted response. The resultant pressure means that, at low tide, the tunnel would be subject to an uplift force equivalent to a 2 m head of water, and an allowance had to be made in the buoyancy calculations.

40. The chalk stratum provides an aquifer of potable water and measures were required to ensure the long-term protection of the groundwater. The employer's requirements presented two options for this protection

(*a*) a layer of clay or bed sealing fill compacted around the base of the tunnel to prevent the hydraulic connection between the aquifer and the river water
(*b*) a waterproof membrane which extended over the entire tunnel and trench area.

The designers considered that for option (*a*) the 2 m uplift force would be realized in full as the sealing fill would cause the excess pore pressure to act on the underside of the tunnel base slab only. Option (*b*) allowed a granular fill material to be placed around the tunnel within the trench. It was concluded that this granular medium would allow the excess pore pressure to surround the tunnel, and not act solely on the base slab. The net uplift effect would therefore be reduced. This option was taken forward by the contractor as the method of protection of the aquifer (see Fig. 10).

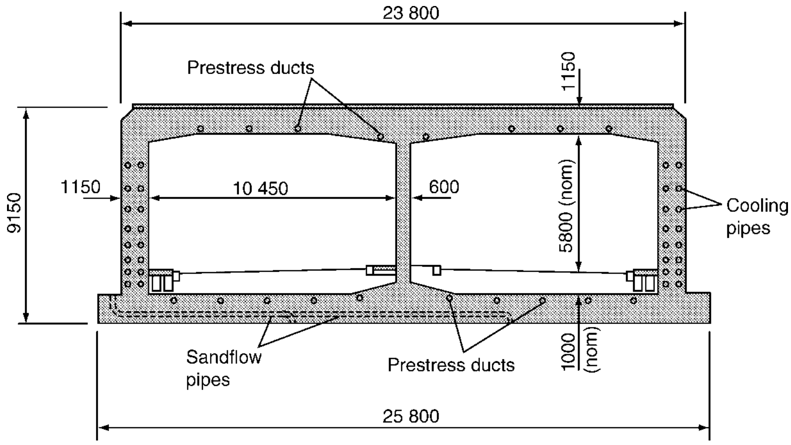

Fig. 9. Cross-section of immersed tunnel (dimensions in mm)

Structural analysis

41. The resulting member thicknesses from the buoyancy considerations were 1200 mm for the base slab and 1150 mm for the outer walls and roof slab. These dimensions are substantially thicker than those that would be required structurally to accommodate the loadings on the tunnel section. These loadings comprise: the dead weight of the structure; hydrostatic pressure; fill materials; traffic loadings; temperature differentials; and accidental loadings which included seismic loading, vehicle collision and ship and anchor impact on the tunnel roof.

42. In accordance with the employer's requirements, the structural elements were designed using limit state principles to BS 5400.[1] Where BS 5400 and its associated BD Notes were found not to be applicable, reference was made to BS 8110,[2] BS 8007[3] and CIRIA Report 91.[4] The structural analysis of the tunnel cross-section was conducted using the

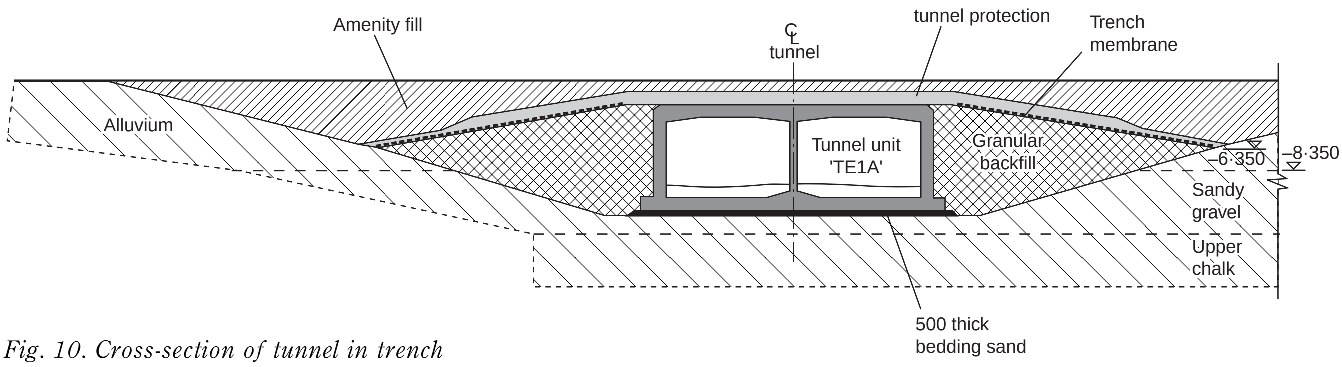

Fig. 10. Cross-section of tunnel in trench

plane frame analysis program Raamwerk, which is a bespoke program developed by TEC. The structure was modelled as a two-dimensional plane frame structure on an elastic foundation. Due to the type of foundation to be employed, uneven tunnel support was considered, both in the transverse and longitudinal directions.

Watertightness, durability and design life

43. The employer's requirements had stated that the tunnel should be watertight to the extent that any leakage would not be detrimental to the durability, serviceability or the aesthetics of the works. The Medway Joint Venture's proposal to achieve this was to omit the external membrane and, in its place, produce effectively watertight concrete. This required considerable liaison between the design and construction teams as the basic principles which needed to be considered were

(*a*) the specification of a durable, relatively dense, impermeable concrete
(*b*) resistance against chemical deterioration of the concrete
(*c*) controlling of early-age thermal cracking
(*d*) prevention of excessive tensile stresses due to creep shrinkage or uneven settlement
(*e*) correctly detailed and constructed watertight joints, both longitudinal and transverse.

This integrated system (a technique never before used in the UK) leads to an effectively watertight structure consistent with the required design life of 120 years.

44. The design and construction teams combined to undertake the sampling of materials, testing and analysis of results to develop a suitable concrete mix design, not only for the immersed tube section but for all aspects of the works. The control of early thermal cracking would be largely dependent on the Joint Venture's proposals to employ concrete cooling techniques, although the methods of detailing and construction of the section would also be extremely important.

45. Differential settlement of the immersed tube could occur due to the nature of the foundation and the structural analysis designed for this. To limit the stresses that could build up longitudinally, each tunnel element is formed as a number of discrete sections or units, and in the case of the Medway Tunnel, each 126 m long element was made up of six 21 m long units, and the 118 m long TE3 was made up of five 21 m long units and one 13 m unit. Between each unit are specially formed spigot and socket type joints—dilatation joints—which allow some articulation to occur, but which work as shear keys (see Fig. 11). The longitudinal reinforcement is not continuous across the dilatation joint, and waterproofing of the joint is by means of a specially designed flexible waterstop. This has steel plates bonded along both sides to which are attached foam strips. Injection tubes located at regular intervals along the length of the waterstop allow resin to be injected through the foam strips, after the concrete has cured, thus sealing any water paths. The prestressing cables which run the length of each element are cut at each dilatation joint after the tunnel is in place to allow the tunnel to articulate.

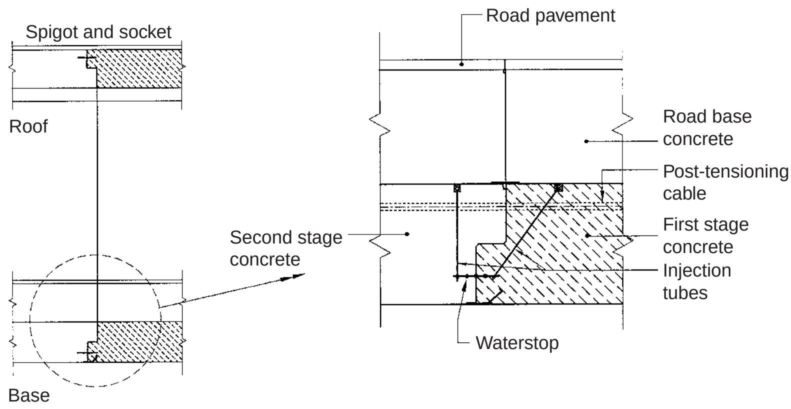

Fig. 11. Dilatation joint detail

46. Detailing of the reinforcement for the tunnel section accommodated the three-pour construction sequence of base slab followed by the central wall and finally the outer walls and roof as a single concrete pour which was fundamental to the durability of the completed structure. This sequence, together with the short unit lengths, reduced the early-age thermal cracking which could occur due to concreting of the outer walls and roof of the structure.

47. The immersion joints at each end of the 126 m long elements, which allow the initial underwater connections to be formed, were designed to act as dilatation-type joints in the permanent condition. Each immersion joint is made up of a Gina gasket, which is connected to a steel frame around the outer perimeter of the tunnel cross-section, which enables the primary seal to be made. The Gina gasket is designed to follow settlement and to remain watertight at the same time. The permanent seal is formed by the Omega profile which is clamped to the same steel frame as the Gina. The Omega profile can also follow settlement, but after testing for watertightness of the profile, infill concrete was cast in the base and wall voids at the joint. A number of large steel dowels were cast into the base slab concrete to act as the shear key between adjacent elements. For the roof infill only a fire-resistant layer of shotcrete was placed for nominal protection of the seals.

Tunnel trench and backfill

48. Before the immersed tunnel could be installed, a trench needed to be dredged in the

river bed between the east and west banks. The depth of the trench was such that no part of the completed tunnel structure, including a 1 m thick layer of rock protection, would be above the existing river bed level. Excavation was through the overlying alluvial clay and sandy gravels and into the grade V/VI chalk. At the tunnel low point, at mid-river, the founding level for the tunnel was 18·5 m below the mean water level, and the trench itself was approximately 12 m deep.

49. As stated previously, groundwater within the chalk stratum gives rise to an excess pore water pressure at low tide which affected the buoyancy of the immersed tunnel section. To combat this it was necessary to provide backfill materials with sufficient permeability to allow the pore pressure to envelop the tunnel and not act on the base slab alone. The sand material which was to be used for the founding of the tunnel had already been selected by the contractor and had a permeability of $k = 2 \times 10^{-4}$ m/s. The designer specified that the granular material for the general tunnel backfill would need to achieve a permeability of $k = 5 \times 10^{-3}$ m/s.

50. The overall trench was covered by an impermeable sheet membrane to protect the chalk aquifer. The membrane extends the full width of the cut trench and is held in place by the rockfill material which protects the tunnel structure against the impact of falling anchors or sunken ships. The placement of this membrane cuts off river water ingress into the gravels and chalk and has allowed the restoration of the original groundwater regime. The membrane was laid with 1 m overlaps between sheets; there is no bonding of the sheets. Thus any excess water pressure which builds up within the backfill materials during the course of the design life of the tunnel can escape through the overlap.

Closure joint

51. During its construction, an immersed tunnel relies on the hydrostatic pressure acting on the 'free end' to maintain the watertightness of the joints. For the majority of immersed tunnel structures the closure joint is constructed between the trailing end of the final tunnel element and the adjacent *in situ* tunnel, with the immersed tunnel supported by props between the two structures. Because of the on-line casting basin arrangement employed at Medway, the eastern cut-and-cover tunnel was not built at the time of the immersion of the final tunnel element, and, in practice, could only be constructed after the casting basin had been

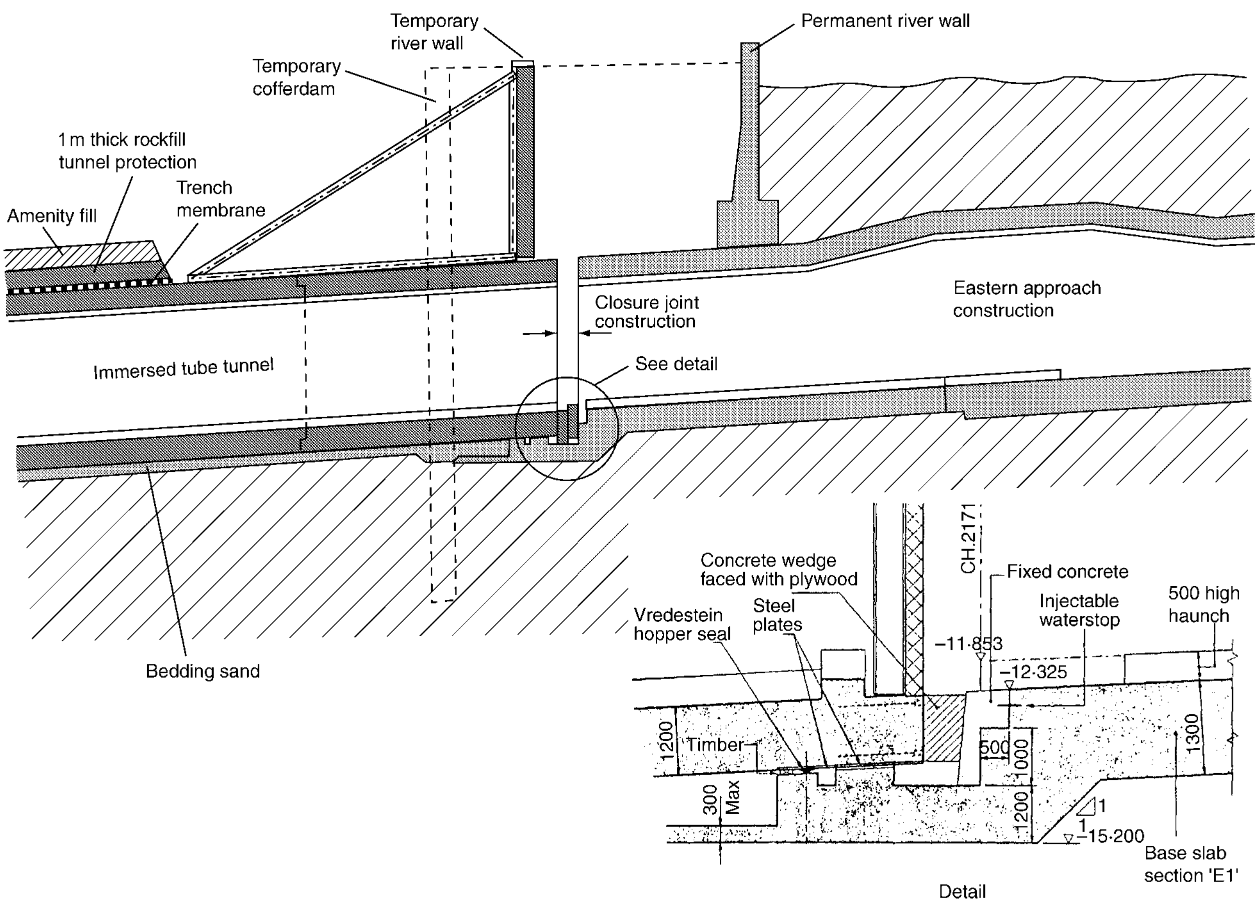

Fig. 12. Closure joint principle (dimensions in mm)

drained. As such, an arrangement was required which would permit the draining of the casting basin area, and at the same time would hold the immersed tunnel in place. An innovative, if not unique, scheme was developed between the designer and the contractor's temporary works teams which involved the sealing-off of the casting basin by the construction of a temporary river wall which was supported on the trailing end of TE3. The base slab of the future eastern cut-and-cover tunnel had been constructed before the casting basin was flooded, and this provided an additional reaction point, for both the temporary wall and the immersed tunnel.

52. The temporary wall needed to achieve the design flood level height of $+6{\cdot}2$ m above datum to fully protect the casting basin area. At the position of the temporary closure the founding level of the tunnel was at an elevation of $-13{\cdot}6$ m and the roof of the tunnel at $-4{\cdot}4$ m. Thus the majority of the temporary closure was over 10·6 m in height across the width of the tunnel. Alongside the outer walls of the tunnel element the wall extended to the founding level and was over 21 m high (Fig. 12).

53. The implications of this temporary structure required considerable analysis of the permanent structure and a significant increase in the amount of reinforcement steel to support the various anchorage points for the wall. The amount of prestressing for TE3 was also significantly more than that for TE1 and TE2, and the requirement to maintain the temporary wall while the eastern cut-and-cover tunnel was being constructed meant that the cutting of the prestressing cables was delayed. The implications of this are discussed later.

Eastern approach

54. The eastern approach structures, which included 260 m of cut-and-cover tunnel and a further 130 m of open approach, were formed mainly within the confines of the casting basin area which had been drained following the immersion operations (Fig. 13). During the early stages of the contract period the Medway Joint Venture negotiated with the adjacent landowners to increase the site area on the eastern river bank. Although the tender designs had shown diaphragm walls for the eastern cut-and-cover tunnels, the contractor determined that a combination of open cut with combi-pile retaining walls would be a more economic solution for the casting basin, with the cut-and-cover tunnels constructed 'bottom-up' within the

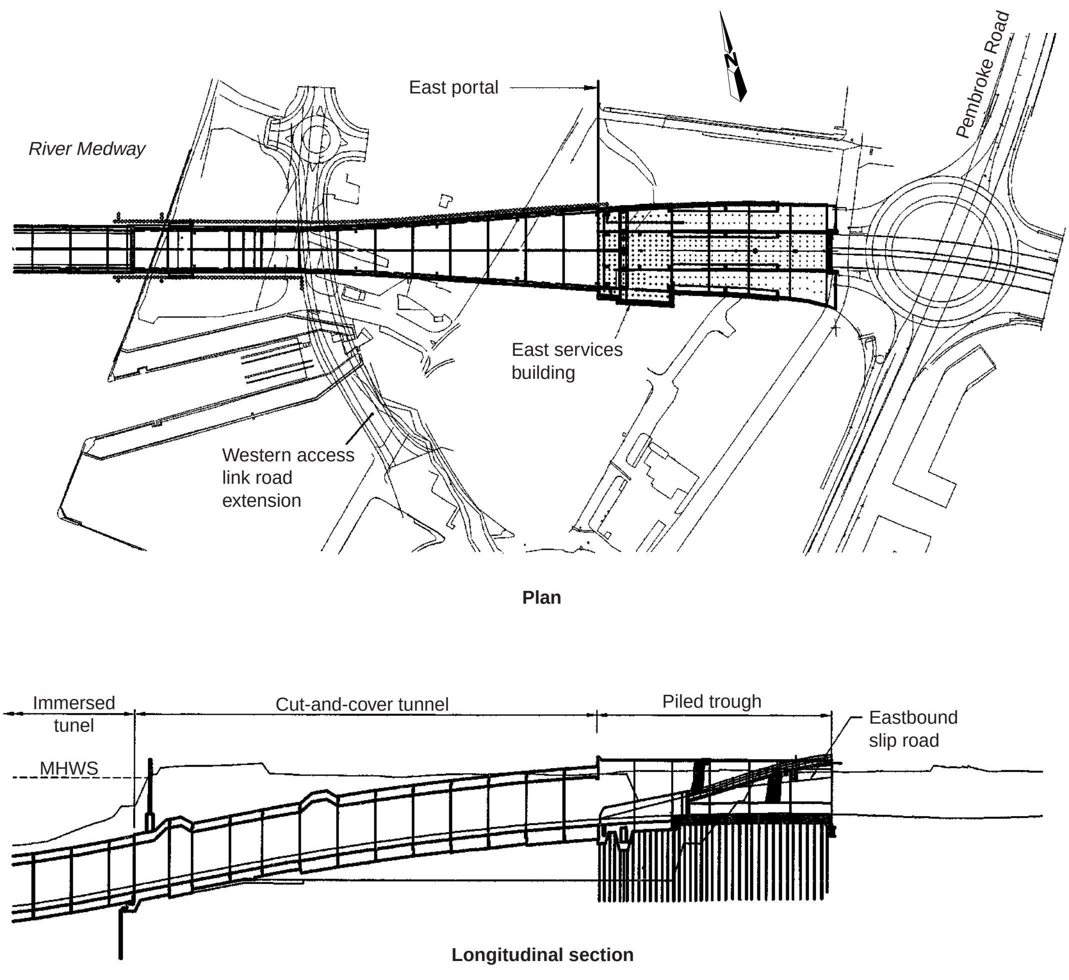

Fig. 13. Plan and profile of eastern approach

excavation. The combi-piles were temporary works only, and were not used in the permanent design.

Cut-and-cover tunnel

55. The basic tunnel structure is similar to the immersed tube section, and in construction utilized the same formwork. The resistance to uplift forces is also counteracted by extending the toes of the base slab of the structure so as to pick up the weight of the fill above. The principles for achieving watertightness of the cut-and-cover tunnel were also the same as the immersed tube, with dilatation joints formed at 20–25 m centres, and a construction sequence of base slab, central wall, and finally outer walls and roof as a single pour, with cooling techniques employed in the final pour.

56. Towards the eastern portal the overall tunnel width increases to accommodate the slip roads which connect with the Pembroke Road interchange. At the portal itself each tunnel bore has an internal width of almost 20 m (see Fig. 14). In these wider sections the safety against uplift is provided by a heavier base slab section than the standard section employed elsewhere. At the portal the base slab attains a thickness of 2 m.

Open trough structure

57. The first 45 m of structure immediately outside the tunnel portal is located in the former casting basin; to the east of this the trough structure was constructed on fill over the batter to the casting basin, and then in cut to the end of the contract area at Pembroke Road. The initial joint between the cut-and-cover tunnel and the base slab of the open approach was designed as a dilatation-type joint which allowed articulation between the two structures. Beyond this the trough was designed to act monolithically with roughened construction joints employed in the base and wall slabs and continuous reinforcement between adjacent sections.

58. The structural form of the trough section is a piled slab with outer retaining walls that support the main cut, and two inner lines of retaining walls which accommodate the slip roads from the main carriageway to the Pembroke Road interchange (see Fig. 15). Watertightness of this final part of the works is by means of a sheet membrane. The base slab has toes which extend beyond the line of the outer retaining walls to assist in the resistance to uplift forces. The piles, which are founded in the underlying chalk, were designed to support the trough structure but also have a tension capacity to resist uplift.

Technical complications

59. Construction of the immersed tunnel and its approaches was achieved satisfactorily, but some technical complications had to be overcome. Mostly, these were of a relatively minor nature, but for the immersed tunnel one inter-related set of circumstances required remedial measures to be adopted and is of particular interest.

Fig. 14. Completed eastern portal

60. The set of circumstances referred to was complex, principally involving the following

(*a*) the total amount of settlement of the immersed tunnel elements
(*b*) the temporary closure arrangements at the east end of TE3 to allow the casting basin to be drained
(*c*) the sequence of the cutting of the post-tensioning cables at the dilatation joints of TE3
(*d*) the grouting of the post-tensioning ducts after the stressing of the tendons.

61. The problems which were experienced manifested themselves as tension cracking of the outer wall of TE3 and some tearing of the concrete nib of one dilatation joint (Fig. 16).

62. The immersed tunnel elements were founded on a hydraulically placed sand directly overlying the dredged surface of the chalk stratum. Short-term settlement of this sand was

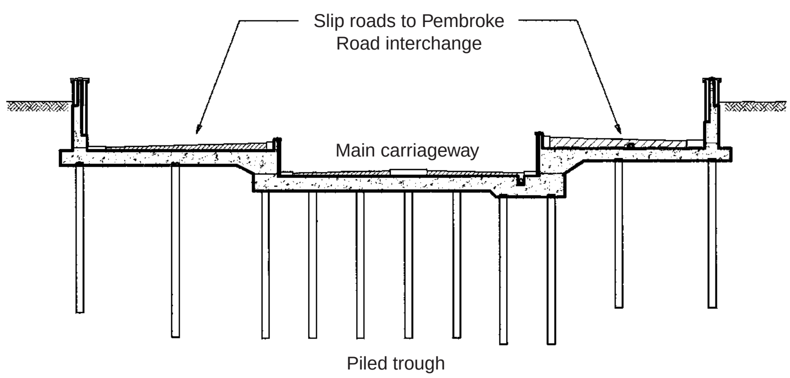

Fig. 15. Cross-section of piled trough structure

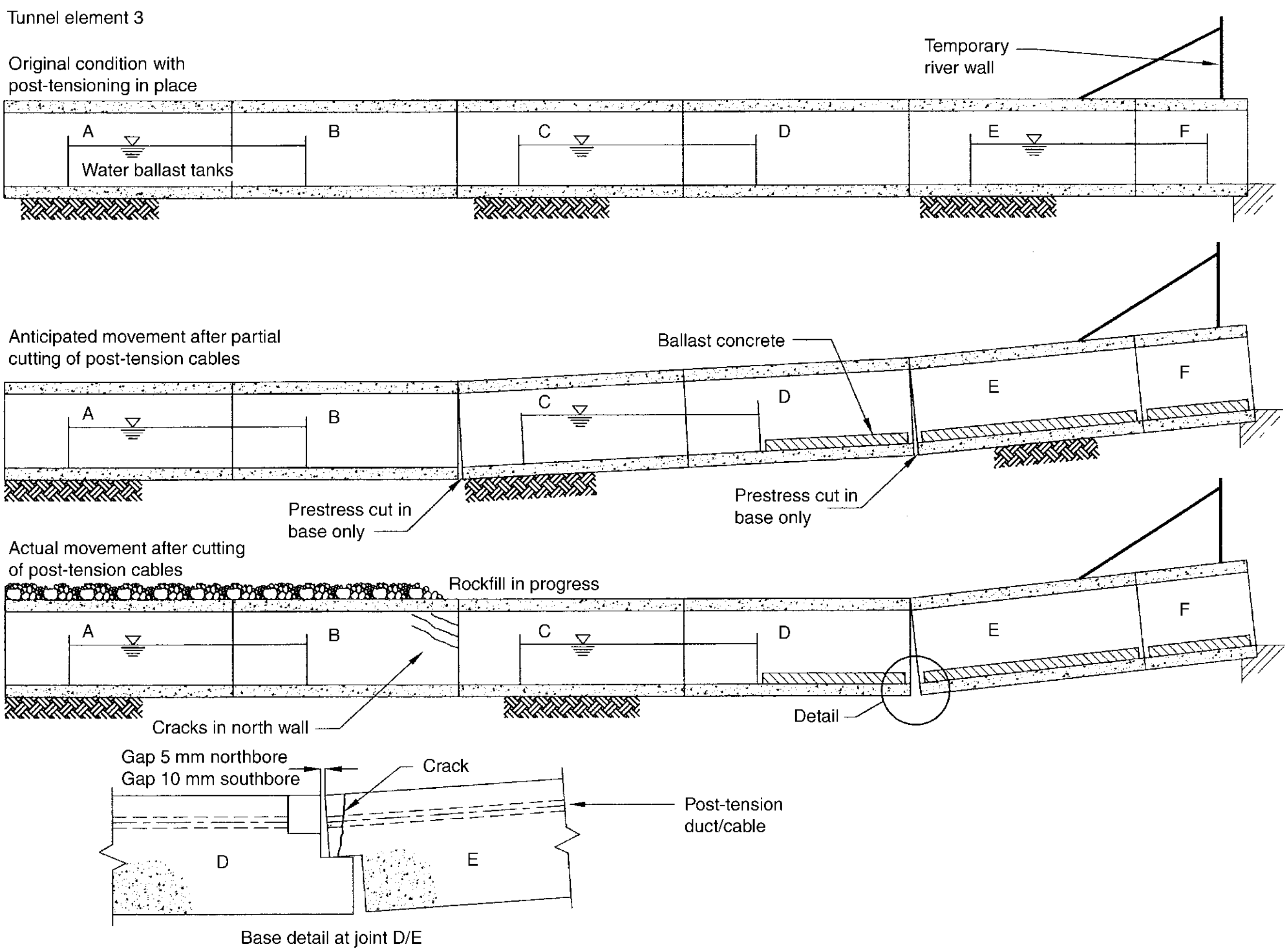

Fig. 16. Settlement movements of TE3

considered to be predictable and to take place very rapidly, with the longer-term settlement being minor. The chalk is a competent stratum which would also be expected to have a small long-term settlement characteristic.

63. The tunnel elements were initially set high to allow for the predicted short- and long-term settlements. At the casting basin end of TE3 the element was set 30 mm high, above a concrete sill. A rubber seal between the sill and the base of the tunnel element prevented leakage into the casting basin. A steel-plated stop was provided to ensure that if greater-than-predicted settlement did occur, the seal would not be crushed. In the event, settlement of all the elements was greater than predicted. The east end of TE3 came to rest on the stop plate and the remainder of the element continued to settle differentially by a maximum of a further 80 mm.

64. Since care had been taken during construction to avoid contamination of the sand bed by silt, the reason for this degree of settlement is not known for certain, but is possibly associated with the nature of the chalk stratum combined with the tidal lag within the chalk aquifer. This tidal lag will have induced cyclical reversal of flow of water within the sand foundation layer and may have resulted in some of the sand being drawn into the interstices of the chalk. The particularly free-flowing nature of the sand used for the bedding would aid such a process.

65. The casting basin closure wall above the east end of TE3 was anchored back to the roof of TE3, putting the whole of the roof slab of the element into longitudinal tension. This required the temporary post-tensioning to be maintained in the roof slab. After the initial founding of the element, the post-tensioning in the base slab was cut at the normal time; however, initially, it could only be cut at two dilatation joints because of the locations of the temporary water ballast tanks which prevented access to the remaining joints. Hence, temporarily, the elements were partially released into 42 m long units which were still held at their tops. Rotation due to differential settlement was thus concentrated at two dilatation joints for this element, resulting in greater-than-predicted movement at these joints, although their design rotational capacity was not exceeded. It was later realized that some leakage of grout had occurred at several of the base slab box-outs at

the dilatation joints during the grouting of the post-tensioning ducts. This grout had effectively locked up the dilatation joint and some local tearing of the joint nib occurred, close to its outer edge, at one of the released joints. The shear capacity of the joint was not jeopardized and no leakage resulted. The cracks were sealed by specialist grout injection.

66. Of more concern were the diagonal tension cracks which developed through the upper part of the outer wall of TE3, at one of the released dilatation joints, and which experienced leakage. After careful investigation it was concluded that this was caused by a combination of racking of the element, due to greater settlements occurring on the south side over part of the length of the element, and the leverage being imposed on the dilatation joint by the 42 m long section. Analysis of settlements indicated a relatively hard point in the foundation under the element, providing a fulcrum for this leverage.

67. The leaks in the outer wall were sealed using grout injection and most of the remainder of the post-tensioning was cut at the dilatation joints as soon as the construction process would allow. Once this was completed the element became free to behave in its permanent design mode, with some redistribution of stress able to occur. There was no subsequent cracking or leakage. The exception to the cutting was at the dilatation joint nearest to the east end of the element. With the combination of a short end unit (13 m compared with the standard 21 m long units), the amount of settlement experienced, and the hard sill support, it was deemed prudent to leave the post-tensioning in place and allow the end unit to act as a single 34 m long section. Tension reinforcement was incorporated into the ballast concrete to ensure whole-life tension capacity across this joint.

68. The prime cause of the complications experienced by TE3 is considered to be the excessive settlements, exacerbated by the particular temporary conditions. The temporary loading conditions alone would not have caused the tunnel any distress.

Mechanical and electrical installations

69. The design procedures for the M&E installations were the same as for the civils designs, with TAP submissions required from the designers for approval by the engineer before detailed design and construction could proceed. Mott MacDonald developed the M&E concepts which were detailed by the Joint Venture's subcontractors—Crown House Engineering—to suit their particular plant. The TAP documentation produced by the subcontractor was reviewed by the designer before submission to the engineer. The concepts of the M&E design and installations are outlined in the following subsections.

Power supply and distribution system

70. Two independent high voltage supplies are provided to the main services building which is located adjacent to the tunnel portal on the west side of the river. For practical and economic reasons these supplies are extended through the tunnel to a secondary services building alongside the eastern portal. Low voltage supplies are provided by transformers at each building. To reduce the effect on the tunnel in the event of a power supply failure, the electrical loads are connected equally to the two supplies. In addition to this, essential loads such as emergency lighting and communications are connected to an uninterruptible power supply system of batteries housed in the main services building. Backup is also provided by a diesel generator.

Tunnel ventilation

71. A longitudinal ventilation system is provided by banks of jet fans located in raised niches in the tunnel roof slab at each end of the 720 m long tunnel. The design of the system was carried out in accordance with the recommendations of the Permanent International Association of Road Congress (PIARC), and fulfils two primary objectives: under normal operating conditions it maintains an acceptable environment for tunnel users; and in emergency conditions the ventilation moves smoke away from users who are trapped in the tunnel.

72. Under normal free-flow conditions the fans operate to enhance the vehicle-induced air flow in the tunnel. The system is monitored and controlled by carbon monoxide and visibility sensors located within the tunnel which cause the fans to kick in when prescribed levels are achieved. In the event of a fire the fans blow smoke in the direction of normal traffic flow. If contraflow is in operation at the time of the fire then the fans blow the smoke to the nearest portal. The system has been designed for a 50 MW fire with a 20% redundancy in the one-way traffic operating condition.

Tunnel lighting

73. The lighting for the tunnel was designed in accordance with BS 5489.[5] The design allows for the safe use of vehicles entering the tunnel from a relatively high ambient light level. This is achieved by having high lighting levels at both the entrance and exit from each bore (Fig. 17). The lighting is arranged in four zones of diminishing intensity from the portal, followed by an interior low level and a high intensity zone near the exit portal. The lighting level is monitored by photometers and controlled by the environmental control and plant monitoring system. The basic fluorescent lighting for the interior zone is dimmed at night.

Drainage system

74. Sumps are located at each tunnel portal and at the low point at the mid-river. Each sump is provided with three duty submersible pumps and one standby pump which discharge surface runoff via isolating and non-return valves into the River Medway. Detectors are arranged to switch off pumps in the event of any significant spillage of hazardous materials in liquid form. Such material is collected by floating skimmers or directly by specialist tanker vehicles.

Communications, controls and surveillance

75. Three telephone systems are provided within the tunnel

(*a*) an emergency telephone system, similar to a motorway emergency system, located approximately every 50 m along the length of the tunnel and connected to Rochester police station
(*b*) a tunnel operator's system for communications between prescribed locations within the tunnel and the main services building
(*c*) smoke control telephones provided in control panels at each of the four tunnel portals and linking the control panel, the services building and Rochester police station; each smoke control panel also contains a dedicated line to 999 emergency services.

76. The project is provided with a CCTV system of fixed cameras within the tunnel, and pan, tilt and zoom cameras on the approaches. The video signals are transmitted to a new control room at Rochester police station, which also accepts information on plant monitoring. The environmental control and monitoring system regulates the following

(*a*) air pollution
(*b*) tunnel ventilation and control
(*c*) portal luminance
(*d*) tunnel lighting and control
(*e*) sump and override control
(*f*) services building plant
(*g*) systems links
(*h*) traffic control.

Alarms classified as urgent are sent to Rochester police station and non-urgent alarms are sent to Kent County Council headquarters at Maidstone.

77. The principal means of traffic control is by the use of variable message signs situated in both the tunnel and approach roads. These are similar to those used by the Department of Transport on motorways and trunk roads. The operator control is limited to a maximum of nine pre-programmed road/tunnel closure plans, designed to be operated by single key entry with passport command.

Fig. 17. View of mechanical and electrical installations, including jet fans in ceiling niches and enhanced lighting at tunnel portal

Interfacing and coordination

78. The overall design-and-construct contract for the Medway Tunnel was to be completed within a period of approximately three-and-a-half years. To achieve this demanding time-scale the design programme needed to reflect the critical path activities identified by the contractor, and considerable liaison was required between all parties.

79. An early deliverable required by the engineer was the new roundabout at Anthony's Way on the western end of the project area. The completion of this facility was seen as ensuring safe access for construction traffic employed on the west bank site from the light industry area of Anthony's Way. The design methodology, and the submissions and approvals procedures for the Medway project, were described earlier in this paper. In practice the Anthony's Way roundabout design established the guidelines for all subsequent aspects of the project, whereby the designer and the contractor needed to ensure that the proposed scheme was fully acceptable to both parties before the agreed submission was issued to the engineer for his approval. Any delays in approval or resubmission of documentation would impact on the overall construction programme.

80. The complete detailed design process is probably best illustrated by that of the immersed tube elements. The initial construction activities on the east bank of the Medway concentrated on the excavations for the casting basin, which, following the start of the contract in July 1992, took approximately one year to complete. During this time the design was progressed on the immersed tube structures. As indicated previously, the Joint Venture undertook commercial considerations during the early phases of the contract to determine their materials sources. Tests then needed to be carried out on concrete mixes to establish the most suitable for the tunnel in terms of durability. These decisions affected the concrete

densities that could be used in the buoyancy calculations and hence impacted on the detailed design programme and drawing production for the structure.

81. Approval for the design methodology had been granted with the engineer's acceptance of the technical approval in principle document. The production of detailed drawings was subject to input from the contractor in terms of his detailed construction methodology, and also the temporary works facilities that needed to be incorporated into the immersed tube for the flotation and immersion operations.

82. These detailed drawings included the number and details of the prestressing cables which run the length of each element, bulkhead details, buoyancy tank layouts, access and survey tower locations, details of the towing anchorages that would be attached to the structures, the 'nose and chin' arrangements which would be used to connect adjacent elements under water plus the jacking facilities at the trailing end of each element, and finally the various attachments on the roof slab of TE3 to support the temporary river wall. In addition, information was required from the M&E subcontractor in terms of space provisions for the various cabinets and panels that would be installed in the walls of the completed tunnel. The construction drawings were subject to many iterations between designer and contractor before submission to the engineer for his approval.

83. In August 1993, concreting of the first base slab of the immersed tunnel was carried out, 13 months after the start of the contract. In September 1994, the first element was floated out and immersed in the River Medway.

Conclusions

84. It is clear that the overlap between temporary and permanent works associated with immersed tunnels makes this form of construction particularly suitable for the design and construct approach. The Medway Tunnel project has demonstrated that, with close liaison and flexibility between the various parties, the full benefits of design and construct can be realized. It is highly unlikely that a conventional engineer's design project would show such a range of construction methods as those used on the Medway Tunnel, where different techniques were employed in close proximity to each other. Credit must be given to the client (Kent County Council) and to the engineer (Symonds Travers Morgan) who developed contract documents which allowed flexibility for the designer to produce innovative schemes, and the contractor to use cost-effective solutions, but which did not compromise the interests of the client or the fitness-for-purpose of the completed project.

85. The teamwork ethic which developed between Mott MacDonald and the Medway Joint Venture was probably best illustrated when technical complications arose during the construction. The close liaison ensured that amendments to the design were fully compatible with the construction methods favoured by the site team. The full cooperation between all parties ensured that additional work was conducted expeditiously and efficiently, with no delays to the overall programme. In every respect the Medway Tunnel project must be considered to be a success.

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