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Broadmeadow Estuary Bridge: Integration of Design and Construction

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Abstract

The Broadmeadow Bridge carries the M1 Motorway Bridge over the Broadmeadow Estuary immediately east of Swords in Fingal. The bridge was designed between 1993 and 1999 and was constructed in the following period 2000 to 2003 as part of the Lissenhall section of the Northern Motorway Contract No 1. The paper reviews the special multidisciplinary needs arising out the environmental issues particular to this site, most notably the natural habitats, landscape, wildlife and residents. The bridge design and construction therefore had to take special account of the ecological balance that exists at the estuary. The integration of the design with the construction methods and the associated environmental mitigation measures are described. The bridge has a number of unusual features including a curved soffit deck, minimalist piers, 2-pour concrete cellular post-tensioned insitu deck, push launching and cantilevering methods of construction, white concrete parapets and a temporary access jetty. The use of stainless steel reinforcement to enhance the durability of key elements is described. The design and installation of an external post-tensioning tendon system, thought to be the first use post launch in Ireland, is described also. The procurement method of the road and bridgeworks is described together with the incorporation of a post-tender supplemental agreement to allow use of the push-launch alternative construction method. A review is given of the Contractor’s innovative system of temporary works used to facilitate push launching over the estuary is also included. The successful combination by Arup of expert multidisciplinary services to solve a unique set of environmental constraints posed by this challenging infrastructural project is summarised.

Broadmeadow Estuary Bridge – Integration of the Design & Construction

Introduction

This major river bridge, completed in June 2003 across the Broadmeadow Estuary, is situated between Swords and Malahide in North Fingal. Broadmeadow Estuary is a semi impounded tidal lagoon, and at the bridge site consists of intertidal mudflats and salt marsh hosting a variety of unusual plants and sub-aqueous flora. A variety of birds also frequent and feed seasonally in the area and it has been designated as a bird sanctuary. The bridge design and construction therefore had to take careful account of the sensitive ecological balance that exists in this inter-tidal estuary and also had to minimise its potential physical and aesthetic impacts on the immediate vicinity - be they impacts on people, animals or plants. In addition, the confined attractive character of the surrounding landscape required a sympathetic design response.

Client Fingal (originally Dublin) County Council appointed Arup Consulting Engineers in 1993. Arup subsequently carried out a Crossing Feasibility Study (Feb 1994), a Preliminary Bridge Design Report (Jan 1999), plus the detailed design and construction supervision of the bridge. Road design and overall project management was undertaken by the County Council's Roads Design Section. Arup were assisted by various specialist environmental advisors acknowledged at the end of this Paper. The original ecological studies for the Estuary were commissioned by the Client's Parks Department.

The Bridge Site

The Broadmeadow Estuary Bridge is located on the Airport to Lissenhall section of the M1 Northern Motorway. The estuarial crossing therefore is the key infrastructural link on this motorway, which successfully connects Dublin City, the M50 motorway and the Airport with the Balbriggan Bypass. The bridge site is just east of Swords, Fingal at the upper narrower end of the Estuary, see Fig 1. Malahide is situated to the east, as is the existing Irish Rail embankment, which separates the Broadmeadow and Malahide Estuaries.

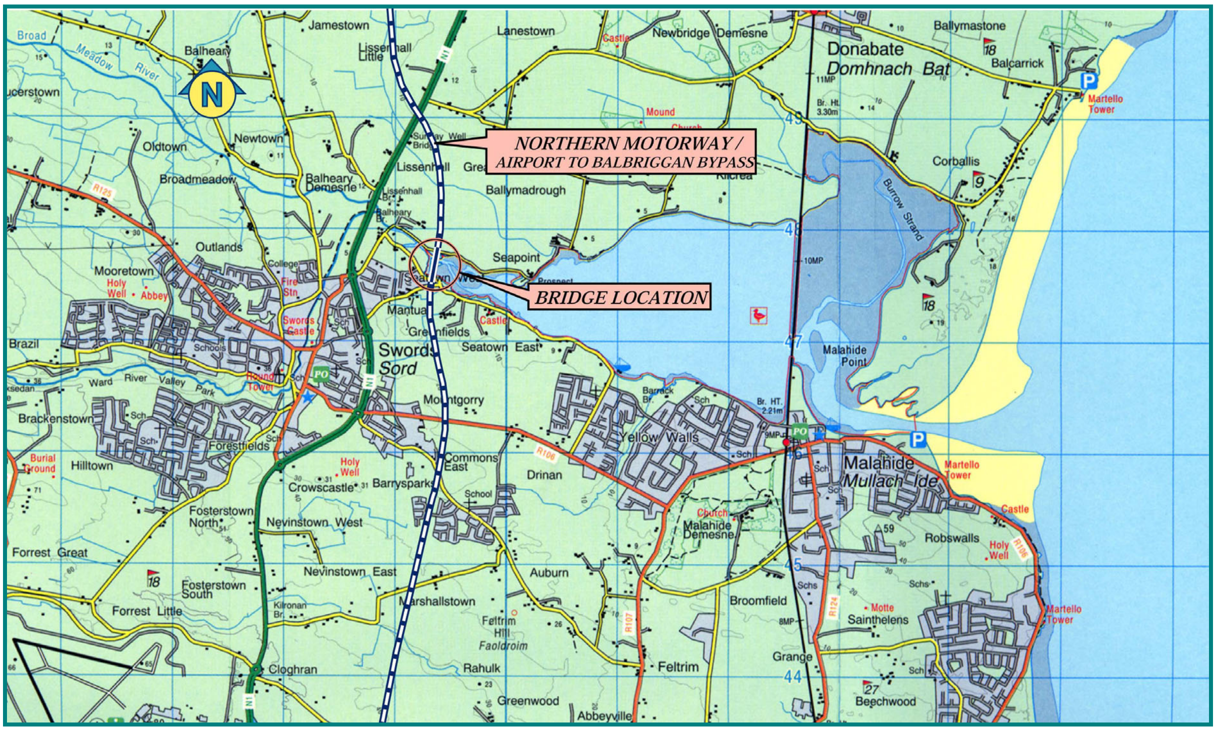

Figure 1: Site Location *Ordnance Survey Ireland Licence Number EN 0002803 © Government of Ireland*

As a result of the presence of the rail embankment Broadmeadow Estuary is a semi-impounded tidal lagoon and at the bridge site is 250m wide between existing shoreline roads. At the bridge the main Broadmeadow River channel is close to the north shore whose flow channel width is 30m approx. The remainder consists of intertidal mudflats and salt marsh, in part locally known as the Horse Marsh. A narrower meandering river tributary has also established itself between mudflats toward the east shore. See Fig 2.

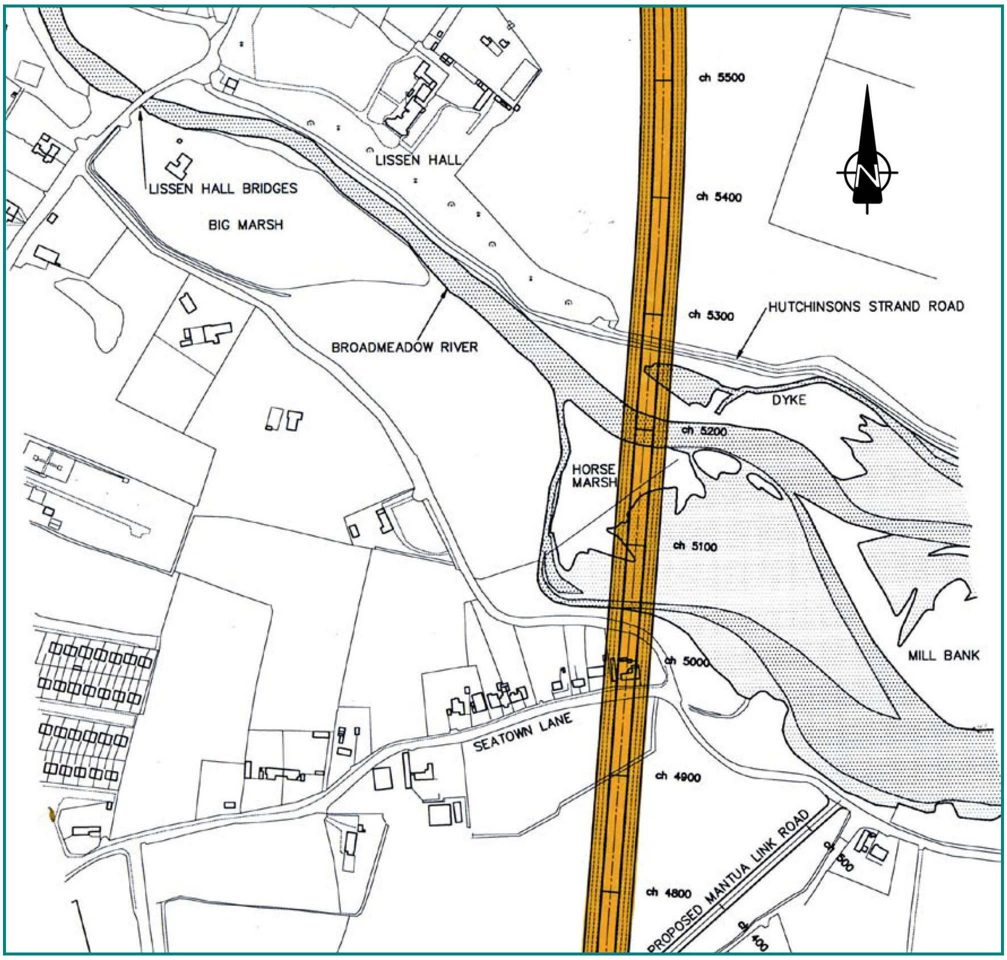

Figure 2: Location Map / Marsh (1994)

There is no great differential between the water level in the inner estuary and the level of the surrounding land. And, because there was a need to maintain only the minimum headroom clearance of 5.3m above the existing shoreline roads, the crossing and associated bridge are deliberately intended to appear low lying relative to the adjacent, predominantly horizontal, landscape.

The inner estuary bed level is above mean sea level at this location, resulting in a low tidal range in the order of 1.5m –inadequate for navigation but ideal for water sport amenity purposes. This shallow water depth however was a severe limitation precluding the use of floating construction plant at this site.

Traffic Arrangements on the Bridge

The bridge cross-section will accommodate two separate motorway carriageways as follows, see Figure 3:

- At opening: 2 x 3.75m wide running lanes, a 3.65m wide raised median, plus 1.0m and 1.4m wide hard shoulders;
- Long Term Median Widening: 3 x 3.75m lanes plus adjusted hard shoulders.

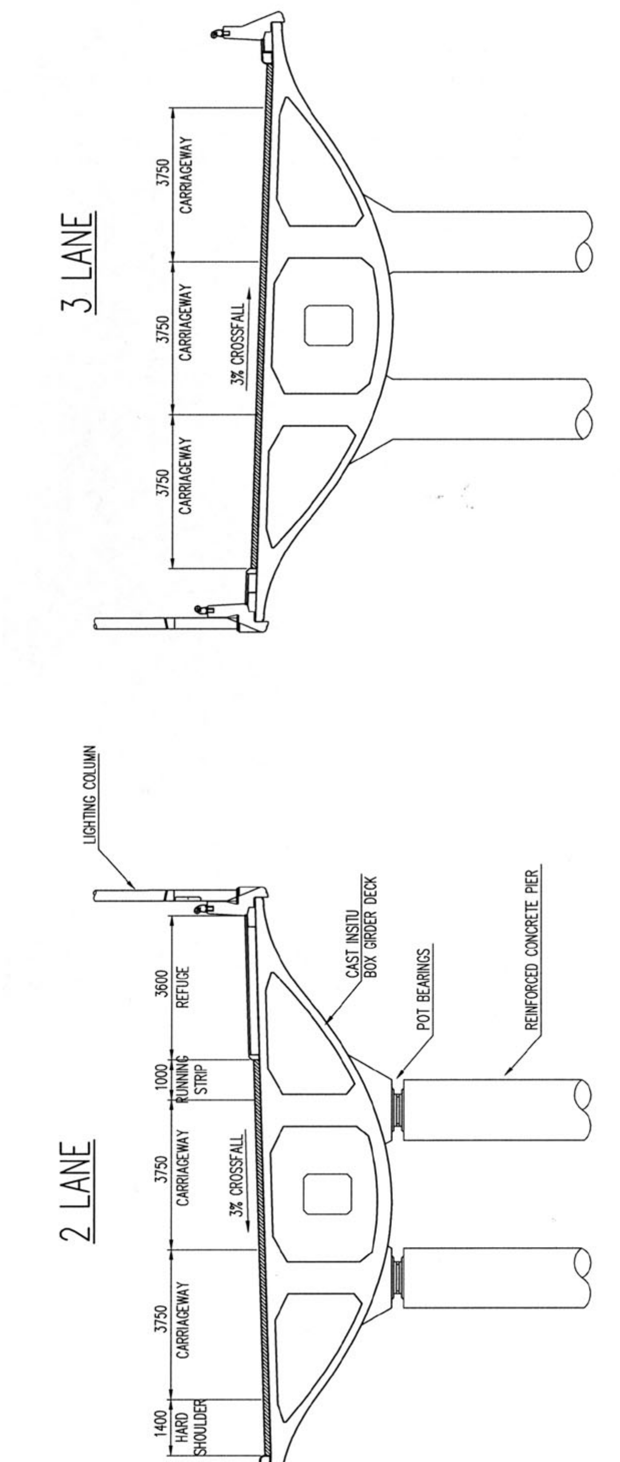

Figure 3: Bridge Section

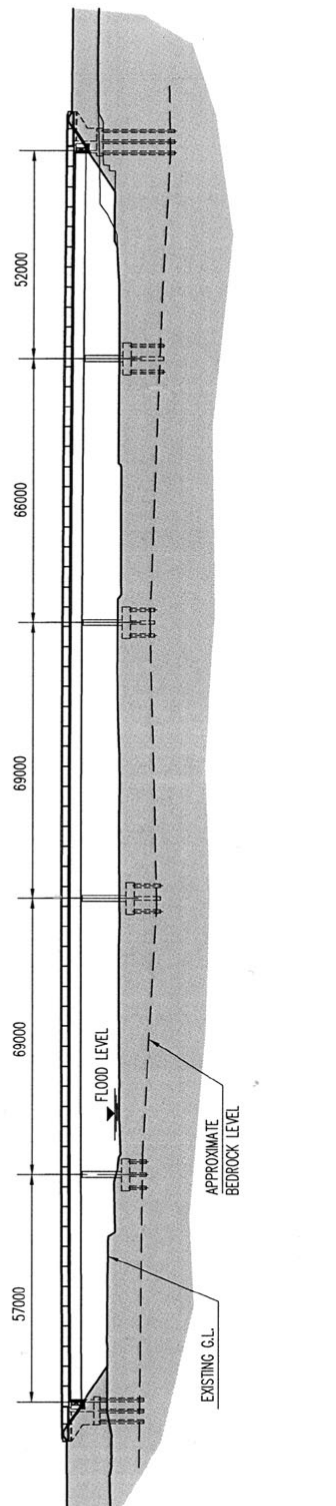

Figure 4: Bridge Elevation

Because the road scheme had been designed adopting a 15m wide grassed median there was ample space to separate the carraigeways onto two independent bridge deck structures. A 6.6m wide air-void therefore runs the full length between the decks allowing light and rain to penetrate to estuary bed level. The change from the two to three lane configuration in the future will be achieved by reducing the width of the raised median and adjusting the shoulder and lane positions. The design of the structure and its associated detailing therefore had to allow for this future lane adjustment without causing undue disruption or requiring major alterations.

Previous Studies

The Arup Feasibility Report, June 1994, examined the engineering feasibility of alternative bridge (multi-span, girder and cable-stayed), embankment and tunnel proposals (submerged-tube, cut + cover, and bored types) for the site. The associated costs, environmental benefits and construction impacts were examined and compared. The need to integrate a sensitively chosen bridge design into the low-key horizontal nature of the estuary landscape was clearly identified.

At the Feasibility Report stage it was recommended that on balance a high quality 5-span concrete girder bridge solution should be adopted as the basis for further design. It was also recommended that detailed restrictions be placed on methods of construction within the Contract Documents for procurement so as to limit the potential for undue negative construction impacts. It was accepted therefore at this early stage that particular emphasis was also to be given in the design to the proper selection of appropriate bridge construction methods in response to the need to preserve sensitive natural habitats.

Environmental Mitigation Measures

Following the publication of the Environmental Impact Statement by Fingal County Council for the motorway scheme in 1995 the bridge scheme was brought forward.

During the development of the bridge design and the preparation of the Contract Documents a range of special design features was included to mitigate potential negative impacts. These were integrated into the overall design by Arup during the various design stages, and are discussed as follows:

Flora and Fauna

At the planning stage, the principal nature conservation issues were defined by the 1994 classification of the Swords/ Malahide Estuary as a candidate Special Protection Area (EU Directive 79/409/EEC) in terms of the Directive on the Conservation of Wild Birds. The primary reason for this designation, as advised to Arup by specialist advisors Natura Ltd, is the ornithological interest of the estuary. There are also other significant ecological interests such as the variety of semi-natural habitats, the vegetation and flora and the intertidal fauna in the inner part of the estuary. The tidal mudflats in the estuary hold a variety of waterfowl species. The numbers of Brent Geese visiting the area each winter is of international importance and the mudflats around the mouth of the Broadmeadow River are used for feeding by a wide variety of wading birds at various times of the year.

The large herd of mute swans is also a nationally significant feature of the Broadmeadow area and is highly valued by the local community, although their normal feeding areas are somewhat downstream from the bridge site. The avoidance of a cable-stayed bridge solution with its associated high pylons and multiple, relatively thin, stays was seen as a sensible measure due to the hazard these were thought to pose to flying swans, particularly at dusk or dawn.

Referring to a pre-construction aerial view in Figure 5, the most significant botanical issues and their mitigation measures are:

- The presence of a transition zone between freshwater marsh and saltmarsh containing some rare plant species worthy of preservation; mitigation measures included the prevention of construction plant access across the mudflats/ marsh area; the plan area of the permanent pier foundations and their excavations was minimised; bridge pier measures were designed to prevent inadvertent release of suspended solids to the estuary receiving waters;

- The presence of a dense stand of the intertidal plant Ruppia Maritima in a narrow dyke at the northern side of the estuary, see Figure 2; the dyke contains the most diverse and abundant faunal communities in the inner estuary. Mitigation measures included the positioning of bridge piers and foundations away from the line of this dyke;
- Affects of shading which may cause reduced light incidence and rainfall under the bridge -- the area effected however will be small in the context of the total area of salt-freshwater marsh available; mitigation measures included the provision of a light well between the two decks for their full length, and the selection of a vertical road alignment to increase the available height under the bridge;

Figure 5: Aerial Photo

A different bridge location 300m to the east towards the Mill Bank area was rejected on the basis of greater visual and ecological impacts, increased bridge length of 100m approx., and even greater access difficulties across the estuary bed. The mudflats at Mill Bank were considered to be the most favoured intertidal feeding area for birds in the inner estuary and it was decided that this area should be avoided.

Landscape/ Visual

Much of the predominantly agricultural landscape surrounding the estuary is of a 'low key' visual quality. Arup's specialist landscape advisors Brady Shipman and Martin consider that it is generally perceived as a largely horizontal landscape with a predominance of low or distant skyline, punctuated only by the taller or more elevated trees and vegetation of the surrounding skyline. See Figs 6 and 7.

A variety of developments had taken place around the fringe of the inner estuary. These include bungalow developments, higher density housing, and the older Lissenhall and Newport Houses. Many of these have significant existing mature screening but there were a small number of properties for which varying degrees of visual impact could potentially arise. Potential visual impacts on the newer industrial developments were also noted and assessed.

Figure 6: View looking South

Figure 7: View looking West

The principal challenge faced by Arup and their consulting bridge architect Wilkinson Eyre of London, was to design a structure which, in its visual form, would blend as harmoniously as possible with the low-lying maritime nature of the landscape. In order to minimise obstruction of the views out over the Estuary from the adjoining shoreline roads and land, Arup worked closely with the architects to devise an elegant concrete bridge form with a slender horizontal deck, with slim and rounded supporting piers, and with a curved underside suggestive of the profile of a boat running at constant depth for the full length of the bridge. As the photos here suggest the design enhances and softens the visual effect of the decks in skyward views from the estuary beneath. In longer views the side cantilevers of the decks cast the curved soffit into shadow thus reducing the apparent visual mass to the observer. In particular the curved boat-shape deck soffit is considered to be appropriate to the maritime nature of the site.

An important aspect of the EIS consultation process was the design team’s ability to demonstrate to the public the likely visual appearance of the proposed new bridge within the context of the landscape. A 2.5m x 2.5m scale model of the inner estuary was commissioned within which the bridge crossing and associated embankments were inserted. This permitted both long and shorter views of the bridge from the estuary to be easily visualised and assessed in a tactile way. Left on public display in the Fingal County Council offices this model, plus the supporting photomontage images, played an important role in gaining acceptance for the scheme.

Amenity

Walkers make considerable use of the southern bank of the Estuary which has been configured by Fingal Co Council’s Parks Department as a linear park all the way from Malahide to the neck of the Estuary. Views by the public from underneath the bridge therefore gave rise to the need for a high quality bridge design.

Road Traffic Noise

It was the policy of the designers to mitigate as far as practicable the effects of any additional road vehicle noise on receiving properties. There are a small number of such properties close to the footprint of the crossing which in particular benefit from the various bridge noise abatement measures adopted. Solid 0.9m high bridge parapets were incorporated to baffle direct noise emanating from vehicles. These match the raised earthen berms positioned on the approach embankment verges, which yield an unbroken noise screen for the full length of the crossing. In addition noise generation was damped at source by the provision of porous asphalt surfacing throughout which greatly reduced wheel noise, and associated spray in wet conditions, the latter also benefiting drivers on the motorway.

Design of the Bridge

The Design Concept

The Arup Preliminary Design Report Jan 1999 recommended that a high quality 5-span concrete girder bridge solution should be adopted for construction. In essence this required a deck to span a maximum of 69m in the central marsh area, reducing to 52m in the landward end span. The main viewing directions from the shoreline roads are at a skew angle to the line of the motorway, which indicated the need to offset the piers between each deck by about 8m. This also helped to position the north end piers so as to avoid the Ruppia dyke on the north shore and the Broadmeadow River channel itself. The piers are at right angles to the decks at all locations, but the offset pier positions suggest a skew effect, although this is not observable in long views across the estuary. The abutments for both decks are in line. The actual spans adopted are 52m- 66m- 69m- 69m- 57m giving a total deck length of 313m to centreline of bearings. See Fig 4. This span configuration also minimises removal of habitat at the critical fringes of the marshes.

The Piers

The supporting circular RC pier stems are 1.5 metres in diameter and spaced four metres apart to allow maximum visibility when viewed from the foreshore. These columns were positioned and designed structurally to simultaneously support the 69m deck spans and to optimise the required 3.2m bridge depth.

Each deck is articulated to permit longitudinal sliding over stainless steel mechanical pot bearings at the end abutment positions and at the landward pier positions. The two central piers are designed to be cast integrally with the supporting piers thus requiring no mechanical bearings. This arrangement has the advantage of eliminating the need to provide for maintenance and inspection and potential bearing replacement at the inner pier heads where access would have been very difficult over water in the mudflats and marsh areas. In addition because this arrangement places the temperature zero movement datum point at the centre of the bridge it only requires the introduction of sliding bearings as one approaches the landward ends. The central piers and associated piled substructures therefore were designed to resist the lower level of deck temperature expansion force arising locally in combination with the vertical loading. In practice the piers are flexible in relation to the more massive and stiffer deck structure and much of the constrained force is dissipated by bending flexure of the pier stems themselves. By virtue of the large diameter CIP bored piling selected however the forces arising were easily resisted by the pile groups. In fact the pile groups had already been designed to resist the out of balance forces assumed to develop in the deck cantilevering process, and so could easily cope with such translational and overturning effects.

Overall bridge longitudinal stability is provided by the two sets of central piers over the marsh mudflats which are cast integrally into the bridge deck. All longitudinal environmental and braking forces are transferred to and resisted by these central piers. Lateral forces arising are however transferred to all pier positions, and in the end piers the mechanical bearings are designed as laterally restrained guided removable bearings. Each pier stem and base assembly has been designed as a vertical cantilever founded in the limestone bedrock.

Each pier base is formed with a 8m by 9m by 2.2m deep RC base placed below bed level, thus allowing the alluvial silt bed to reinstate itself once construction is complete. Its plan shape is dictated by consideration of self-inertia required to provide stability against overturning forces imparted by the deck in the temporary and permanent cases. The base is also designed to transmit the 50,400 kN total pile reaction as a deep pile-cap. See Fig 8.

The pier stems are relatively flexible at 1.5m in diameter and extend down to the buried pier bases located beneath estuary bed level. The inner estuary environment is partially protected by virtue of the semi-impounded nature of the tidal pattern. Aggressive abrasive maritime splash zone conditions do not arise in this instance. Nevertheless, normal saline, chloride and sulphate conditions have been assumed to exist requiring attention to long term durability. The pier concrete specified is Grade 50 with a 20mm aggregate and a minimum of 400 kgs per cubic meter of Ordinary Portland Cement. Given the difficulty of future access for inspection across the mudflats however, further assurance in relation to potential rebar corrosion was deemed prudent. It was decided to design the rebar within the pier stems as stainless steel to help enhance service life and provide further assurance of stem integrity in the long term. The principal advantage of stainless steel rebar in this context for the designer is its passive nature in resisting rebar corrosion instead of placing total reliance on the as-cast quality of the enclosing covercrete to prevent corrosion initiation. In reality these two mechanisms work together. However, this enhancement came at a cost of stainless rebar of €3,500 per tonne, i.e. up to 6 times the normal ferrous steel rate. In an overall context however the total increase in cost for the limited tonnage of stainless steel used was 2.5% approximately for the overall bridge cost. The principal implication for the Contractor is the need to programme in the longer supply lead-time required for delivery of stainless bar to site, which in this instance was quoted as 12 weeks nominally for large diameter bars.

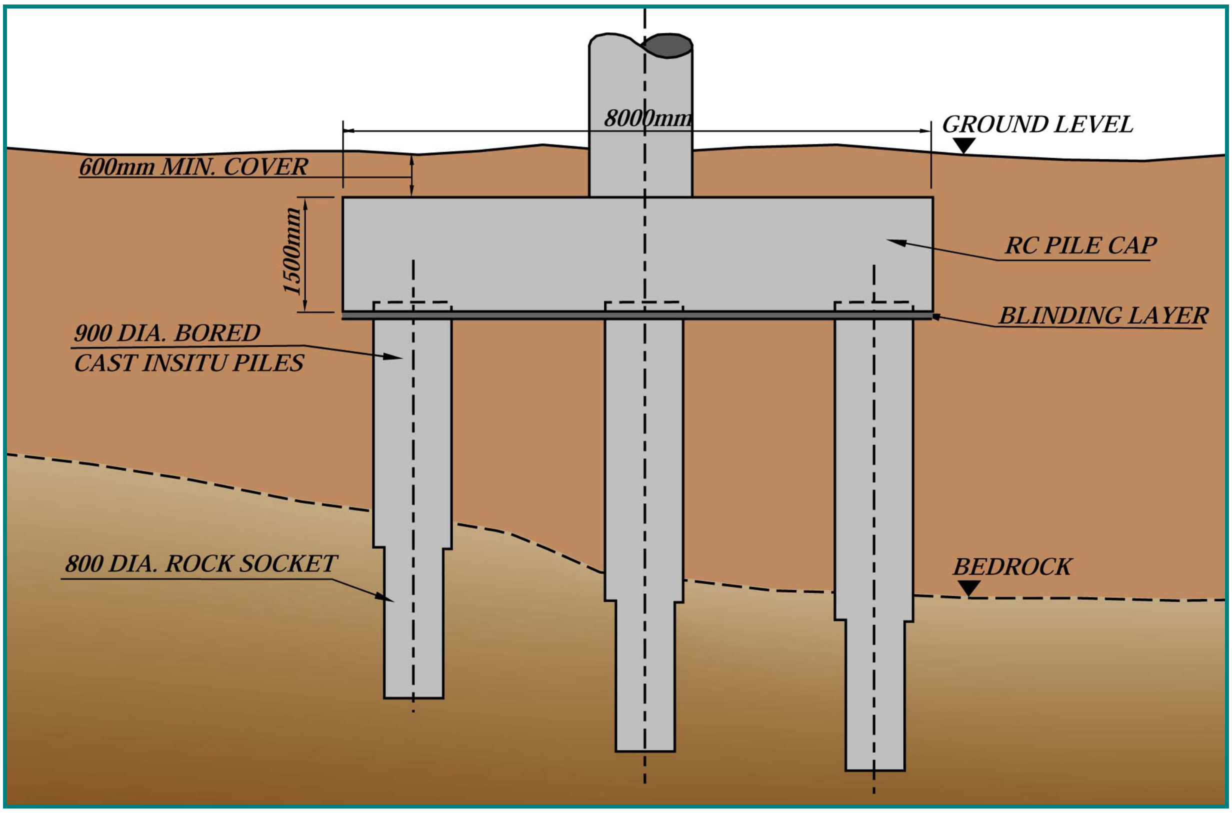

Figure 8: Typical Pier Section

Abutments

The abutments are simple RC structures placed on CIP bored piles. The main feature of the abutments is the provision of end inspection galleries surrounding the deck ends. These house the supporting mechanical bearing, the expansion joints and the post-tensioning end anchors. Easy access is also available for entry to the internal deck voids via security doors placed in the median sidewalls. Grade 50 concrete was used throughout for durability.

Bridge Deck

- The deck is a uniform depth three cell voided concrete girder with a transversely curved soffit extending between the deck parapets. The cross-section of each deck as designed is 14.7m wide in plan and is shown in Figs 3 and 9, comprising the following elements:

  200mm minimum transverse RC top slab spanning between longitudinal webs;

- 2 Nr 2.8m deep longitudinal web beams positioned vertically over the line of the permanent bearings/pier stems. The webs vary in width from 400mm at mid-span widening to 900mm at the pier positions;

- 250/350mm varying thickness RC soffit slab taking a curved profile in cross-section resembling a boat shape. The soffit slab connects each edge of the deck top slab with the underside of the webs with a double reverse curve symmetrical about the deck centerline;
- The two side cells are outboard of the webs and are roughly triangular in section;
- The single longitudinal centre cell is in-board of the webs and is rectangular in shape albeit with a concave downward bottom slab;
- Internal bonded tendons;
- 1.5m wide RC transverse diaphragm beams connect the deck structurally across the pierhead lines yielding a 3.2m depth along the centreline and 300mm at the deck edge;

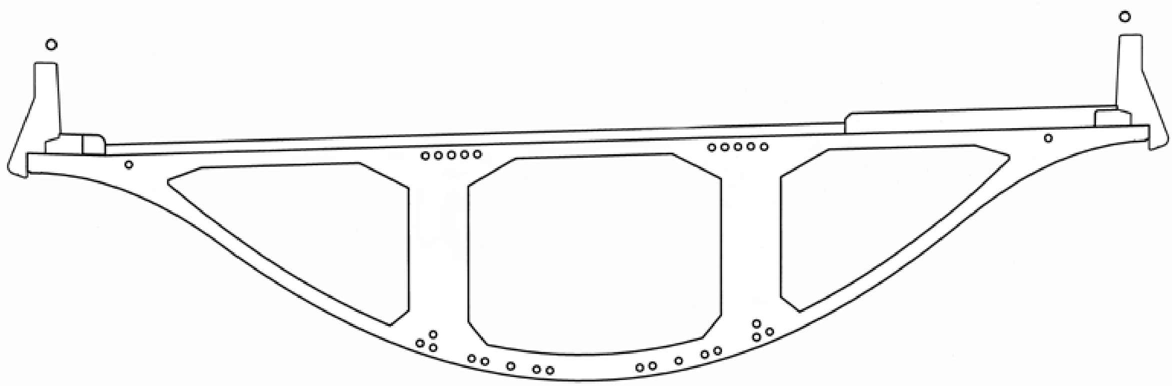

Figure 9: Curved Soffit Deck Section

The deck was designed to take account of the assumed insitu balanced cantilever deck construction process adopted in the Arup Preliminary Report of Jan 1999 proposed as a means of minimising habitat loss within the estuary marsh and mudflats.

The as tendered deck design is post-tensioned longitudinally in conformance with the Class 1 (Combination 1) structure requirements in BS 5400 Part 4, for internally bonded tendons assumed to be protected by web concrete. HA and HB traffic loading was taken from BD37/88 for the assumed lane positions with separate load cases for the future three lane situation. The analysis assumed linear elastic behaviour based on gross section properties, and the analysis was done using the Arup in-house BRILLO 2-D software package. The analyses incorporated the various stages of the assumed construction sequence, including the assumed segment casting cycle, movement of form travellers, environmental effects, and secondary moments (effects progressively built in to the structure with each stage of deck stitch completion).

The conforming design was based on an asymmetric method of balanced cantilevering. The method assumed temporary props on one side of every permanent pier, acting as a strut or tie depending on the direction of the out of balance forces. The segmental temporary props were braced back to the permanent piers and were required to be stressed together down to the pile caps. The asymmetrical nature of this method minimised the out of balance forces and ensured that the permanent piers incorporating conventional pot bearings are always subject to compression axial forces, without uplift or undue rotation.

The method assumed a typical segment length of 4.6m, which is within the range of the current industry standard for moveable formwork travellers. Due to the curved nature of the deck cross section it was envisaged that the segments would be constructed in two separate pours, a soffit pour with cantilevers followed by a top slab pour. This would ensure satisfactory compaction of the curved soffit sections. The segments would be progressively stressed back to the previously constructed segments with 12K15 multiple strand tendons with anchors at each segment joint.

The design assumed construction effectively from one side of the estuary to the other working outward from each permanent pierhead. Completed balanced cantilever deck sections would be progressively stitched together at midspan using bottom continuity tendons installed to carry the superimposed and transient loads of the permanent situation.

Parapets

The 1.25m high vehicle containment parapets used are comprised of a 900mm concrete upstand topped by a proprietary aluminium single rail parapet, see Figs 10 and 11. The composite parapet is designed to normal containment standard in accordance with BS 6779 intended to safely contain errant vehicles within the bridge confines. In elevation the precast concrete parapets are 1.5m high designed to sit down over the thin edges of the deck and have an inclined front face and rounded lower edge to visually soften their appearance. They are cast in Grade 50 white reinforced concrete. This white concrete band over the deck structure ensures that the deck appears less prominent visually in longer views. Solid parapets also help to mitigate road traffic noise outside the bridge.

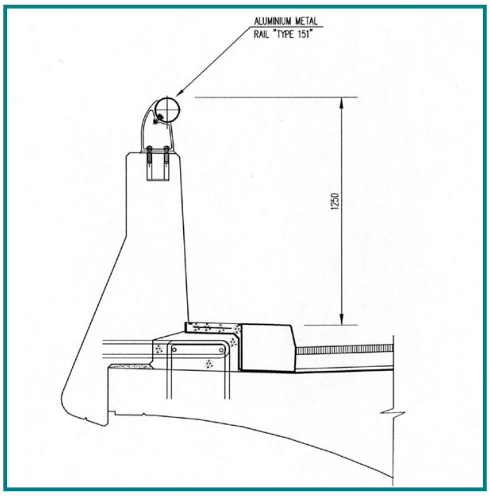

Figure 10: Precast Parapet Section

Figure 11: White Concrete Parapets

The white concrete parapet segments were precast by Banagher Concrete Ltd in workshop conditions using white sand and white cement, cast against metal reusable forms. The 268 Nr x 5m long panels were precast with projecting stainless steel starter bars ready to overlap with similar upstand bars projecting from the deck top slab. The units were propped temporarily on site whilst a rectangular stitch beam was cast insitu to form a moment connection with the deck in the area of the raised verges. The stitch beam is coated with deck waterproofing material to ensure durability.

Foundations

The bedrock geology of the Broadmeadow Estuary area shows the proposed bridge location to be underlain by Argillaceous Bioclastic Limestone of Lower Carboniferous age. This formation consists of lower medium to dark grey fossiliferous muddy limestone interbedded with calcareous shales. It is generally thickly bedded to massive with claybands and numerous fossils. There are many fault lines indicated in this area, but they were relatively poorly defined due to the lack of outcrop in the locality. Drift maps indicated soft alluvial deposits underlain by glacially deposited tills, consisting predominantly of well-graded boulder clays with interbedded water bearing gravel and sand layers.

Site investigation contracts were awarded in Oct ’93 and in Sept ’98 consisting of 13 boreholes with rock cores together with geophysical surveys calibrated back to the local borehole information. On the south side of the estuary the depth of overburden was approximately 5m below estuary bed level, and on the north side the rock head drops to between 6 and 10m locally in boreholes. Weathered limestone rock was evident, with sound rock occurring below the nominal rock level encountered. See Fig 12.

The estuary bed material was composed of soft organic clayey silt and clays with SPT values as low as 3. These organic clays and silts extended for 1.5m below bed level and were recorded as non-plastic to intermediate plasticity with average undrained shear strengths less than 20 kN per sq. metre.

Fine to coarse alluvial gravels containing cobbles were also encountered in the boreholes below the organic materials, with SPT values between 16 to 32 indicating them to be medium dense to dense.

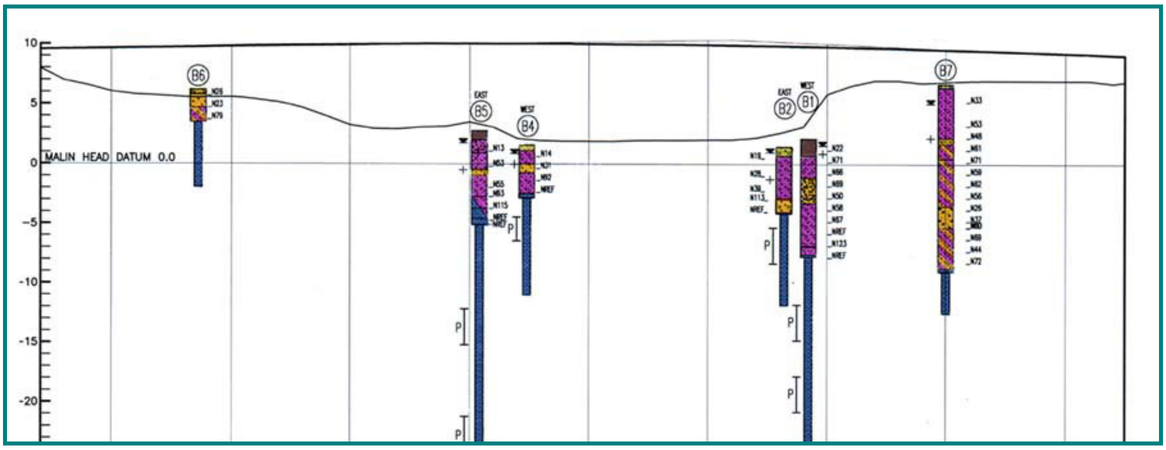

Figure 12: Geotechnical Section

At 3 to 4m below bed level firm to stiff brown boulder clays were encountered exhibiting low plasticity, average moisture content of 10%, and undrained shear strength of 75 to 150 kN per sq. metre.

Silty sandy fine to coarse glacial gravels are located below this level, and are either below or interbedded with the brown boulder clay stratum above. Insitu permeability tests show these gravels to have medium to high permeability, with average angle of internal friction of 41 degrees. Also interbedded in some location were medium dense to dense glacial sands with angle of friction of 36 degrees.

The bedrock is immediately overlain by stiff to hard black boulder clay of low plasticity and undrained shear strength of 300 to 350 kN per sq. metre.

The rock is dark grey to black fine grained slightly to moderately weathered calcisiltite to calcilutite limestone moderately weak to moderately strong. The discontinuities are generally rough, undulating very closely, to moderately closely spaced, with open slightly weathered, occasionally completely weathered joints. In general total core recovery (TCR) was good, ranging from 75% to 100% with an average of 88% while Rock Quality Designation (RQD) values ranged from 0% to 100% with an average of 40%. The Fracture Index (FI) ranged from 2 to 10 in uniform litology with an average of 7.3, while fracture spacing ranged from 0.072m to 0.15m, with an average of 0.11m. These all suggested the rock to be relatively highly fractured, with up to 60% of the core revealing fracture spacing of less than 0.100m. A number of fractures revealed calcite fill and clay infill well below the rock surface. Also the limestone revealed no trend with depth and does not become less fractured with depth. Some areas of non-intact rock were also encountered. In general however the presence of karstic conditions was not supported by the rock core results obtained although bands of weathered rock with poor core recovery were encountered.

The rock was classified as moderately strong to strong based on Unconfined Compressive Strength (UCS) and point load tests although these were considered to be unrepresentative of the rock mass since strength testing was based on the more competent core pieces. The UCS range 27 to 70 MN per sq. metre was therefore taken as an upper bound guide for preliminary design.

Geophysical investigations revealed the bedrock to be undulating in two directions with height differences of 4.5m generally, but with higher values of 7m to 10m towards the north believed to be associated with a Palaeochannel of the Broadmeadow River. Poorer quality shallower bedrock with higher clay mineral content was suggested south of the river by resistivity testing. The northern area revealed deeper bedrock levels.

In general, bridge foundations could either have been carried down to the relatively shallow bedrock or based on the shallower boulder clay/ gravels. There were fears in relation to potential differential settlement of foundations founded within the highly variable interbedded clays and glacial gravels in the overburden. In addition there were fears concerning the highly weathered joint discontinuities in the limestone bedrock. A foundation solution utilising large diameter cast-in place (CIP) bored piling was devised to spread the large load concentrations arising from the piers. A pile group of 12 Nr 900mm Dia rock socketted piles was specified per pier location each with a working axial load of 4200 kN used to transmit the direct and overturning forces arising from the superstructure. Because the rock at the abutments was also reasonably shallow the same strategy was used there except a group of 15 similar CIP rock socketted piles with a working capacity of 2800 kN was used. To prevent cement grout migrating to the estuary waters each pile was specified to have full-length permanent metal casing inserted in tandem with the rotary boring process --- thick walled steel casing was proposed by the Contractor. These casings helped to exclude ground water entering the bores via the gravel layers, and provided additional assurance as to the structural integrity of the permanent pile shaft.

The CIP rock socketted pile foundations, which were required to found within the more competent bedrock, had to take into account the extremely undulating nature of the bedrock and the highly fractured upper layers of the rock. In carrying out the pile installation on site some additional measures had therefore been specified in advance in the Contract documentation:

- to help define the final pile lengths required,
- to predict the actual rock socket lengths,
- to help justify the skin friction and bearing values assumed for the design in each case, and
- to check for the existence of very heavily weathered rock below estimated pile toe levels

Advance rock core probing was specified to obtain 75mm diameter rock core samples below the estimated toe level of each pile group. This was carried out using rock core equipment from within the pier cofferdams. Following the main pile augering each pile toe bedrock exposure was visually inspected using down the hole CCTV. Having identified the nature of the rock and the degree of weathering and rock jointing, Arup then confirmed the actual rock socket lengths required. The tendered socket lengths varied between 2m and 4.5m into sound rock depending on location.

In the area of the southwest abutment in particular some very heavy weathering and fractured limestone was encountered locally at greater depth than anticipated. These issues were resolved by a combination of lengthened pile shafts, reliance on skin friction resistance only and the inclusion of additional piles within the original abutment plan area. Once the problem had been established and defined on site it required a high degree of interaction on site between designer and piling sub-contractor to arrive at a timely and expedient solution. The Contractor was able to devise a suitable piling sequence that allowed the previously established rock coring and visual toe inspection process to be maintained albeit with a conservative approach being taken to working factors of safety for the enhanced pile group.

Bridge Procurement

The bridge was procured as part of the Lissenhall section of the motorway in a single contract. Because of the scale and relative importance of the estuary bridgeworks to overall completion of the Contract however, it was decided to carry out a pre-qualification process in order to establish a list of competent tenderers. Through this process tenderers were alerted in advance to the need to have appropriate specialist bridge cantilevering construction experience and track record on board.

The prequalification process was undertaken under the Restricted Procedure of the EU Works Directive 93/ 37/ EEC. Candidates were asked to prequalify using a questionnaire specially prepared under a range of issues, included amongst which were the following:

- construction experience of balanced cantilever road bridges within the previous five years;
- construction experience of concrete post-tensioned bridges within the previous five years;
- minimum bridge turnover within the previous three years;
- a minimum road turnover within the previous three years;
- availability of technical and managerial staff for the Contract duration.

The design team recommended that the five best qualified candidates of those applying be invited to tender for the road and bridgeworks, thus virtually guaranteeing the ability of the tenderers to undertake the bridge works successfully within the proposed 36 months contract period.

Tenders were received at the end of January 2000 accompanied by bridge construction technical proposals. Following clarifications Arup recommended the acceptance of the Ascon Nuttall Joint Venture Ltd tender for the bridgeworks in the amount of €12.7M (excluding VAT and Preliminaries).

Construction

Substructure

As noted elsewhere in this paper, in order to prevent habitat loss, restrictions were specified in the contract documents to prevent access by construction plant to the mudflat and marsh areas. Also the shallow water depth available meant that construction barge plant could not be utilised. To enable foundation construction to proceed, however, a temporary suspended access jetty was specified in the tender documents, see Fig 13. Further restrictions were listed, in that only discrete steel H-piles could be placed through the estuary bed. The Contractors were asked to design this structure as temporary works based on an Arup performance specification to cater for their selected piling plant requirements. In the event the jetty was also used by the Contractor as a temporary haul route for earthmoving plant, thus fulfilling a dual role and restricting construction traffic to within the site that otherwise may have had to use the public road system. This can therefore be cited as a further positive environmental construction mitigation measure accommodated within the project.

Figure 13: Access Jetty

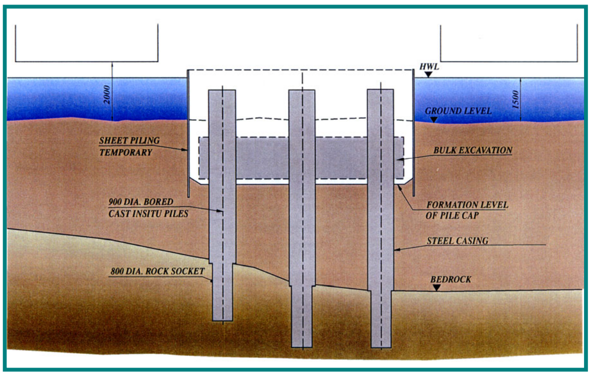

Figure 14: Pier Cofferdams

Also the use of temporary discrete cofferdams for the construction of the piers and their foundations provided maximum protection for the surrounding marsh, minimised habitat loss, and facilitated the "clean disposal" of locally displaced soils off site. See Figs 14, 15, and 16.

Figure 15: Piling Construction

Figure 16: Pier Cofferdams

Alternative Deck Construction Method

The Contractor, Ascon Nuttall Joint Venture Company proposed an alternative 'launched cantilever' method of construction. This was the first time it has been used in this country on this scale. With this system, insitu segments of the curved soffit bridge deck, each 20m average in length, were cast on land and then pushed end-on-end from the south side of the Estuary towards the other, see Fig 17. This was carried out by using large land-based hydraulic jacks, low friction sliding bearings pads and temporary support structures. Due to the curved nature of the deck cross section the segments were constructed in two separate pours, a soffit pour with side cantilevers and internal webs, followed by a top slab pour. This ensured satisfactory compaction of the curved soffit sections prior to installation of the top slab formwork. With the experience gained a segment casting cycle of 8 days average was achieved. Early strength gain was therefore essential to facilitate moving each segment forward quickly. The designers were able to take full advantage of the good early strength properties of OPC concrete, which in the colder winter months became a key factor in the construction programme. Special curing methods were employed such as frost blankets and on occasion warm air heaters within the cellular decks.

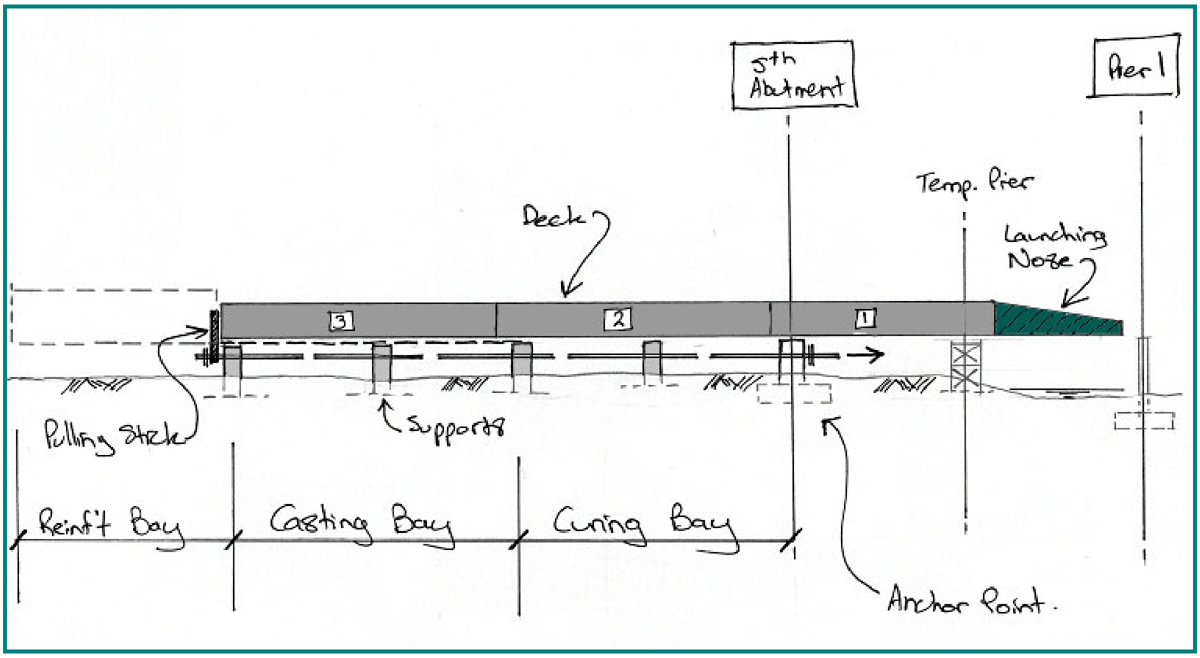

Figure 17: Launch Construction Sequence

Arup carried out a full Category 3 design check on the Contractor's alternative deck design and ultimately approved the design prior to commencement of construction. This process, coming in parallel with foundation construction, required close liaison between Arup and the Contractor's design team to ensure the overall programme was not jeopardised. A cooperative approach by all ensured a successful outcome. The analysis assumed linear elastic behaviour based on gross section properties, and the analysis was done using the Arup in-house General Structural Analysis (GSA) 2-D software package. The output was then compared with the Contractor's analysis which had been carried out by another method. The analyses incorporated the various stages of the construction sequence to build up the complete force envelope, including the segment casting schedule, attachment of the launching nose, varying temporary pier reactions, partial construction of the deck diaphragms during launching, the removal of temporary piers and the installation of the prestress forces. The deck was checked for compliance with the BS 5400 Class 1 structure requirements under SLS permanent loads, and Class 3 for all other load combinations. This was deemed to be a reasonable approach given that the prestress is applied post launch and unbonded tendons remain outside the concrete section.

To cast the deck segments, the Contractor had devised a multi-staged casting bed with travelling cranes, rebar prefabrication, suspended reusable formwork and long-line assembly techniques to produce the complex deck shapes economically and to consistent quality. See Figs 18 and 19.

Figure 18: Deck Casting Bed

Figure 19: Side Cell Formwork

The concrete segments were cast on specially designed retractable curved steel formwork located on the south shore. The gull-wing shaped forms were supported on temporary falsework set on hydraulic jacks capable of being lowered 450mm vertically once the segment overhead had reached, typically, its two day strength. That space allowed the insertion of the horizontal jack attachments necessary to slide the segments across low friction PTFE pads over the support points. This operation was an engineering feat in its own right, which drew on the collective experience of Ascon Nuttall and their specialist design sub-contractors. See Figs 20 and 21.

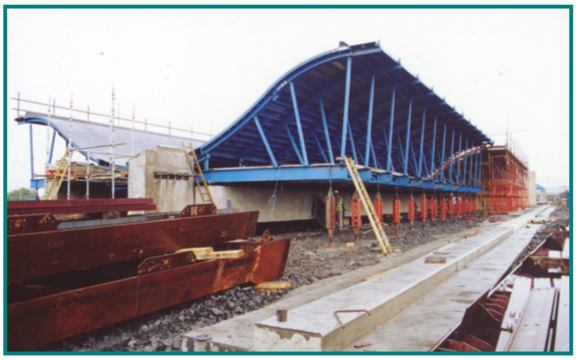

Figure 20: Retractable Soffit Form

Figure 21: Sliding Pads

Deck launching was visually dramatic with unsupported cantilever lengths of up to 35m assisted by use of fabricated steel launching noses. These fabricated steel trusses allowed the deck segments to make contact with the piers earlier than would have been otherwise possible. The deck was launched utilising the reinforced concrete box section. Once the 313m long deck was extended full length the box was then prestressed using 12 Nr full-length 27K15 external tendons located in the cell voids. This is also thought to be the first use of external tendon technology post launch in Ireland on this scale. All prestressed tendons were designed to comply with the latest NRA code of practice for grouted tendons. An advantage of full-length tendons is that the number of anchorages was as low as 48, thereby simplifying and speeding the construction. See Figs 22 and 23.

Figure 22a: Internal Tendons

Figure 22b: End Anchors

Figure 23a: Launch Nose Steelwork

Figure 23b: Launch Process West Deck

Figure 23c: Launch Nose and Temporary Piers

The external tendons were designed as straight multi-strand lengths between deviator diaphragms at third span locations and at the pier positions. The deviators were designed to transfer the resultant prestress reactions vertically to resist the applied loads. Sealed HDPE plastic ducts around the strand contained cementitious grout to provide an alkaline environment for durability.

Figure 23d: Deck/Launch Nose Connection (1st launch)

The curved profile of the soffit meant that it was possible for the deck to rotate about its own longitudinal axis during launching. It was therefore possible for significant forces to develop in the piers should those movements become excessive. A strict regime of monitoring of the movements of the deck and the supporting piers during launching was devised by the Contractor to ensure the safe anticipated movements were not exceeded. See Fig 24. Among the mitigation measures used to control the reactions developed were: moveable counterweights on the deck surface to help control rotation, and the introduction of additional slipper pads on the sliding surfaces to control lateral movements. In reality this monitoring required a large number of people on site especially as the deck increased in length. With the experience developed however it proved possible to launch a 20m long segment in less than 3 hours greatly assisting with the Contractor's programme.

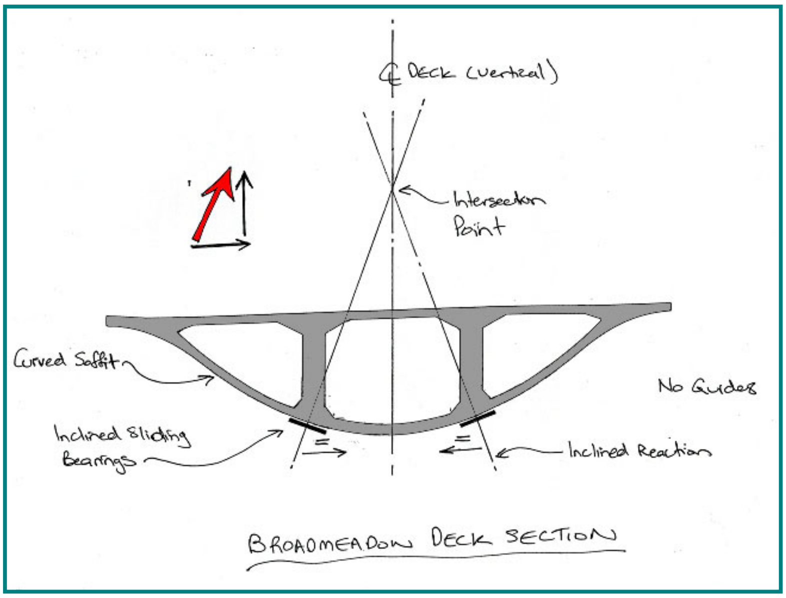

Figure 24: Inclined Reactions

Finishes

Modular mechanical expansion joints were designed and installed at both ends of each deck to cater for seasonal expansion and contraction movements, but also to allow for the longer term creep shortening associated with the deck post-tensioning. For extra durability these joints were galvanised and painted. Removable raised verge cover plates were specified to allow easy adjustment in the future to cater for the third traffic lane along the median. This can be done without altering the cast-in expansion joints.

The adoption of porous asphalt wearing course surfacing as a noise mitigation measure required the incorporation of continuous linear kerb drains to help remove sub-surface runoff rapidly from the deck. These contained drainage slots at the underside of the wearing course but also at drain invert level just above the red sand asphalt protective layer. Drain outlets were cast into the top slab at 20m centres approx. flowing into a longitudinal carrier drain within the deck voids.

The deck top surface was primed and waterproofed with a two coat sprayed acrylic membrane system protected by a layer of red sand asphalt.

Median Lighting Columns

Another significant botanical mitigation measure arising from the Arup 1994 Feasibility Study and the 1995 Environmental Impact Statement related to the potential affects of night-time illumination of the estuary by roadway lights. Such affects were required to be mitigated by ensuring that the lighting apparatus was designed, positioned and angled so as to minimise light over-spill to the estuary bed. The solution devised by Arup for the bridge crossing was to restrict the positioning of lighting columns to the line of the median void. There are no lighting columns at the deck edges, see Fig 25, thus simplifying and improving the bridge appearance. To minimise back-lighting the associated lanterns are restricted to 12m in height and angled upwards and outwards towards the roadway whereby the deck itself acts as a shade over the estuary bed immediately adjacent to the bridge. This principle was also extended to the embankments on the bridge approaches and to the median void on Mantua Road Bridge nearby. This resulted in median lighting columns for a 800m continuous length of motorway centred on the estuary. This approach was fully consistent with the aspiration of having a single visual solution to lighting column geometry when viewed from anywhere around the estuary environs.

Figure 25: View showing Median Lighting (Mudflats Post Construction)

Programme / Opening

The choice of the launched cantilever method of construction and the integration of the complex permanent and temporary works into the overall design were critical for economy and speed. A single steel soffit mould was reused for all deck segments. Bridge construction was ongoing between Autumn 2000 and May 2003 with the overlapping construction of piled foundations, piers, east deck, west deck and finishes across the two decks. By careful attention to rebar fixing and formwork removal the deck casting cycle was optimised down to an average of 8 days per nominal 20m segment. The removal of temporary works and the construction of finishes for each deck were also overlapped to optimise the bridge completion time, see Figs 26 and 27.

Figure 26: Staged Construction

Figure 27: West Deck Launched

A supplemental post tender agreement was offered by the Contractor in Dec 2000 for consideration of adopting the alternative launched construction method. The cost of the deck works was effectively bought out therefore, as was the risk of any associated potential time overruns. This ensured the bridge was constructed on time and within the tendered amount except only for some additional foundation works associated with the bedrock faulting and undulating bedrock surface.

The motorway and Broadmeadow Bridge finished 4 months ahead of schedule and opened to traffic on 27 June 2003, see Fig 28.

Figure 28: View from the Estuary

Summary of Approx Quantities

The Arup tendered scheme comprised the following approximate quantities:

- 10,400 cu m concrete
- 1,450 t reinforcement
- 105 t stainless steel reinforcement
- 350 t prestressing tendons
- 1,280 metres aluminium rail.

The Ascon-Nuttall Joint Venture alternative deck construction method subsequently rebalanced the distribution of these quantities in that significantly extra longitudinal bar reinforcement was needed to launch the deck into position. Less permanent prestress and associated anchoring was needed by virtue of the 12 Nr full-length tendons adopted instead of short tendons anchored at each segment. Also, the volume of concrete was reduced by trimming the member thicknesses in cross-section by virtue of placing the tendons externally to the webs. The weight of stainless steel remained constant.

Figure 29a: Curved Soffit and Median Void

Figure 29b: Bridge Elevation

Figure 29a: Median Void and White Parapets

Figure 29b: Mudflats through Median Void

Conclusions

Because of its estuarial site location and the associated important natural and visual constraints, this bridge design required an individually tailored design and construction strategy. The successful combination by Arup of the necessary expert multi-disciplinary services (natural habitats, bridge aesthetics, geotechnics, constructability and structural) ensured that the challenging set of constraints posed by this site were satisfied. In summary, it is believed that innovation was achieved by the integration of the permanent and temporary works structural designs to arrive at a highly constructible solution for a maritime site with difficult access. The main features of this bridge are:

- the unique form and character of the permanent concrete bridge design utilising a curved soffit deck and minimalist circular piers
- integration of the concrete bridge design into the low key landscape environment
- integration of the temporary and permanent works designs to optimise insitu concrete construction in response to the need to preserve natural habitats
- achievement of excellent high strength insitu concrete quality and white precast parapet units where high early strength was critical to programme
- utilisation of stainless steel reinforcement in critical elements to enhance durability
- successful design of a long-line concrete casting bed facility reminiscent of factory workshop methods, to economically produce complex cast shapes to consistent quality
- use of external prestress tendon technology (first use in Ireland post launch)
- use of a unique launched cantilever construction method (first use in Ireland) – launched R.C. box followed by post-tensioning after launch
- ingenuity of the technically complex temporary works designs and construction geared to a highly repetitive 8 day casting cycle
- completion of a major concrete structure and associated road opening ahead of schedule and on budget.

Part of the Northern Motorway Project, the Broadmeadow Bridge has dramatically shortened the journey time between Dublin and Drogheda, Dundalk and Belfast since opening. It is also a key element in the National Roads Authority motorway system, substantially improving travel times on the important M1 motorway, contributing to the economic development of Dublin and the northeast. It is part of the Government's National Development Plan and was part funded by the EU.

Arup were the lead consultant for Fingal Co Co for the bridge design, procurement and construction supervision. The motorway was designed by Fingal Co Co Roads Department, who also undertook the overall project management.

Acknowledgements

The authors gratefully acknowledge the permission of Mr James Cleary, Senior Engineer Transportation, Fingal County Council, to publish this paper.

A Principal Participants List is attached to this paper detailing those organisations involved in the design and construction, but in addition the authors wish to acknowledge the input, support and assistance of the following:

- Tom Jones, Senior Resident Engineer, Office of the Engineer's Representative who led the bridge construction supervision team for the duration.
- Jim Ward, Chief Resident Engineer for the Northern Motorway Contract No 1.
- James Moloney, Structures Agent and Darren Wren, Launch Manager of Ascon Nuttall Joint Venture.

- All present and former employees of Arup Consulting Engineers who contributed in so many ways over the ten-year period since project initiation.
- Frank Callanan and Elaine Staunton, formerly of Arup Dublin who undertook the geotechnical appraisal and detailed structural analysis, respectively, for the tender design.
- Frank Montgomery Model Maker who prepared a scale model of the inner estuary for public consultation purposes.
- Jorgen Nissan of Ove Arup & Partners, London and Peter Langford of Arup Consulting Engineers for their advice and guidance.

Principal Participants List

DESIGN	
Lead Consultant:	Arup Consulting Engineers, Dublin
Consulting Bridge Architects:	Wilkinson Eyre Associates, London
Bridge Owner:	Fingal County Council
Road Authority:	National Roads Authority
Funding:	National Development Plan and Part funding by EU
Road Design and Project Management:	Fingal County Council Roads Department
Specialist Assistance (EIS, Ecological and Lighting)	Fingal County Council Planning, Parks and Lighting Departments
Internal Lighting Consultant:	Kevin Cleary & Associates, Dublin
Habitat Specialists:	Natura Environmental, Wicklow
Landscape Consultants:	Brady Shipman Martin, Dublin
Site Supervision	Arup and Fingal Co Co Resident Teams

CONSTRUCTION	
Contractor:	Ascon-Nuttall Joint Venture, Kill, Co Kildare
Concrete Supply:	Roadstone Limited, Feltrim
Precast Parapets:	Banagher Concrete Limited
Contractor’s Designer (and Launch Temporary Works):	Robert Benaim Associates, London
Prestressing Sub-Contractor:	Freyssinet UK, Limited
Deck Launch Sub-Contractor:	Freyssinet UK, Limited
Deck Retractable Formwork Sub-Contractor:	Freyssinet UK, Limited
Piling Sub-Contractor:	Murphy Piling Limited, Newbridge
Jetty Designer:	Nuttall (UK), Limited
Metal Parapets	Varley and Gulliver Ltd, Birmingham

Figure 30: Aerial View