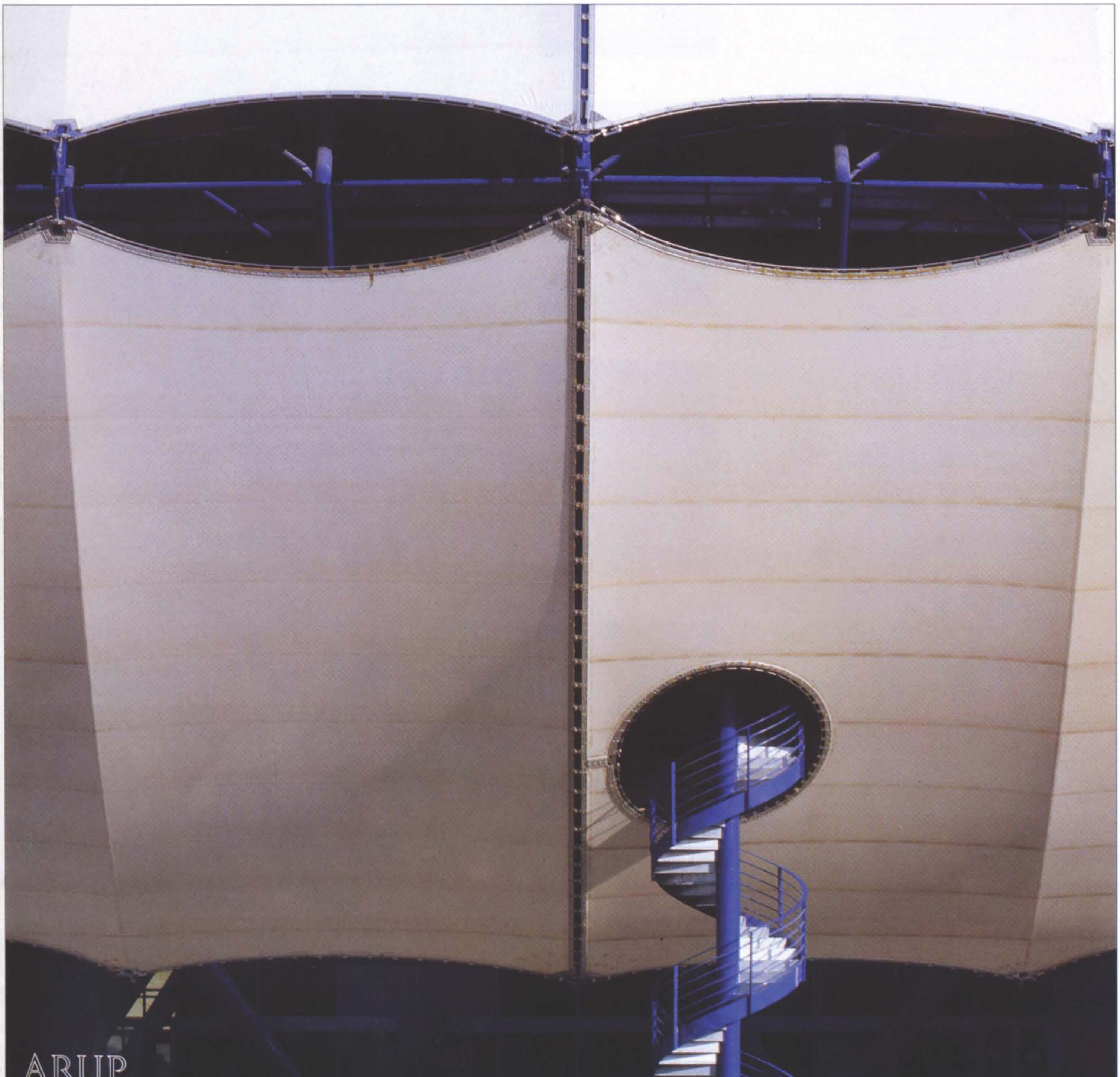
THE ARUP JOURNAL

4/1994



THE ARUP JOURNAL

Vol.29 No.4
4/1994

Published by
Ove Arup Partnership
13 Fitzroy Street,
London W1P 6BQ

Tel: 0171 636 1531
Fax: 0171 580 3924

Editor:
David J. Brown

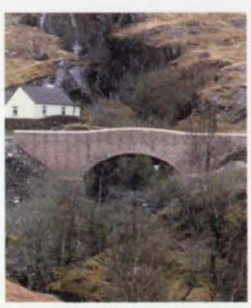
Art Editor:
Desmond Wyeth FCSD

Deputy Editor:
Hélène Murphy

Editorial:
Tel: 0171 465 3828
Fax: 0171 465 3716

Front cover:
Fabric membrane, designed by Arups, on the Deliberatif at Marseille Hôtel du Département. (Photo: Paul Rafferty)

Back cover:
Allt-Ruigh Bridge, Glencoe. (Photo: Jim Burridge)



Note: The photo on p.18 of *The Arup Journal 2/94* captioned as Pagbilao power station in fact showed a model of Shenzhen International Economic Trade Centre, Guangdong, China. The scheme was designed by SOM with no Arup involvement.

1. The completed building from the east: Deliberatif in the foreground, Administratif behind.

Hôtel du Département, Marseille

Bob Lang Hugh Muirhead

Introduction

In early 1990 the French Département des Bouches-du-Rhône announced an open, international design competition for a new local government headquarters in Marseille. 156 entries were received, from which five were selected in April 1990 to extend their proposals. These were narrowed down to two in June, when the jury sat and the design teams presented their schemes in detail.

Alsop & Lyall (latterly William Alsop Architects), with Ove Arup & Partners as engineers and Hanscomb Ltd. quantity surveyors, were successful and announced as winners in July 1990.

The competition-winning design made much of the local climate of Marseille, where people are used to wide temperature variation and strong winds: the notorious mistral is a feature of life in this part of France. Where possible, these natural phenomena were exploited to articulate the form of the building and make a real contribution to how it would function.

The essential elements of the brief were to create 75 000m^2 of office and conference space, (excluding terraces, plant areas and storage), and 1000 below-ground car parking spaces. Also the St Just metro station – well within the curtilage of the site – had to be retained. All this led to a first scheme comprising three rows of office blocks spaced by two atria, and a long, curved-section building, the Deliberatif, to house the council chambers. The blocks were to be tall and thin, so much could be made of natural ventilation and thermal control from buffer zones formed by external corridors and circulation spaces.

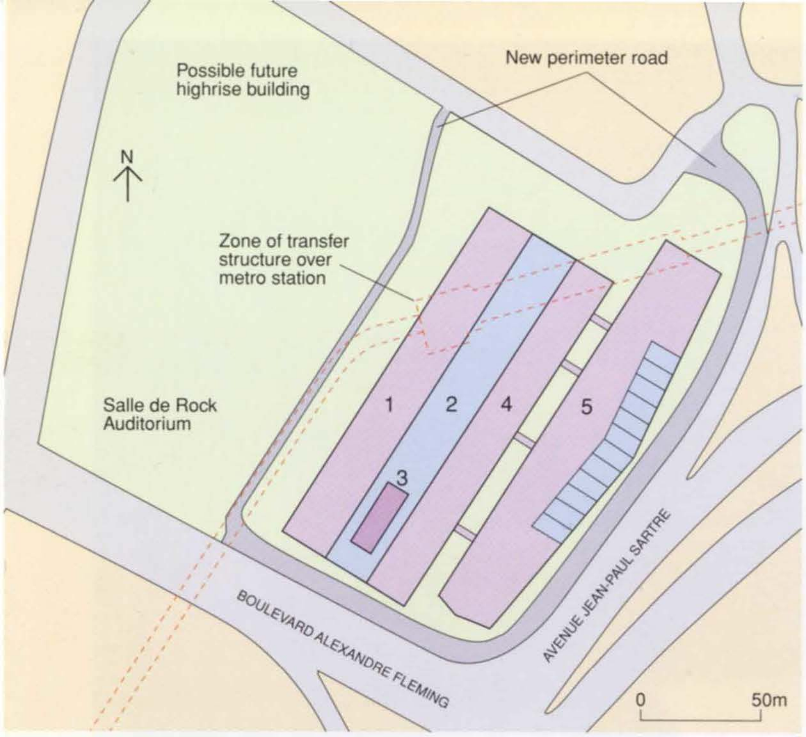
However, building height restrictions introduced after the competition finally called for a much shorter, wider, treatment, using internal circulation. The buffer zones were thus omitted and attention focused on wind effects to assist climate moderation.

By careful manipulation of the building cross-section, pressure profiles and controlled aerodynamics could be grasped and used.

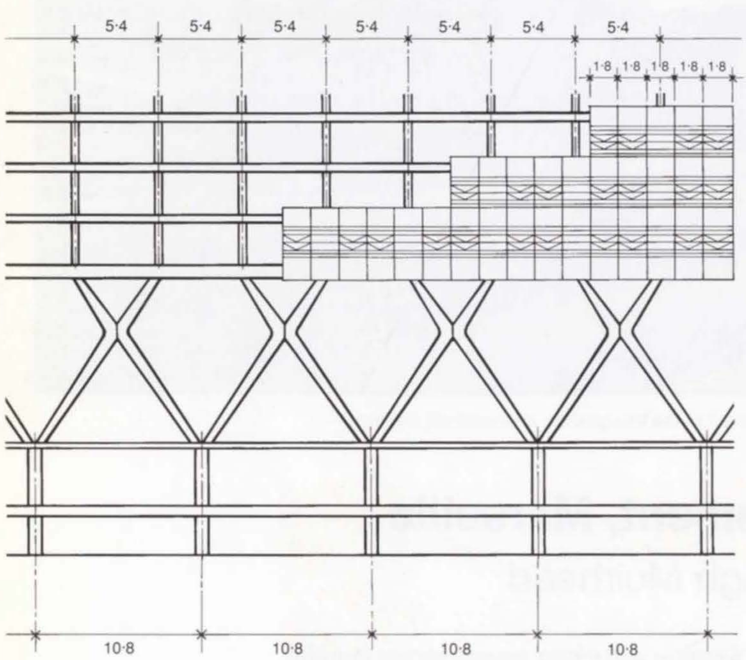
Furthermore, the external environment around such a building mass could be made more hospitable.

As seen today, the building has two major elements of office space, the Administratif; and the long, profiled, Deliberatif, containing the chambers and conference space.

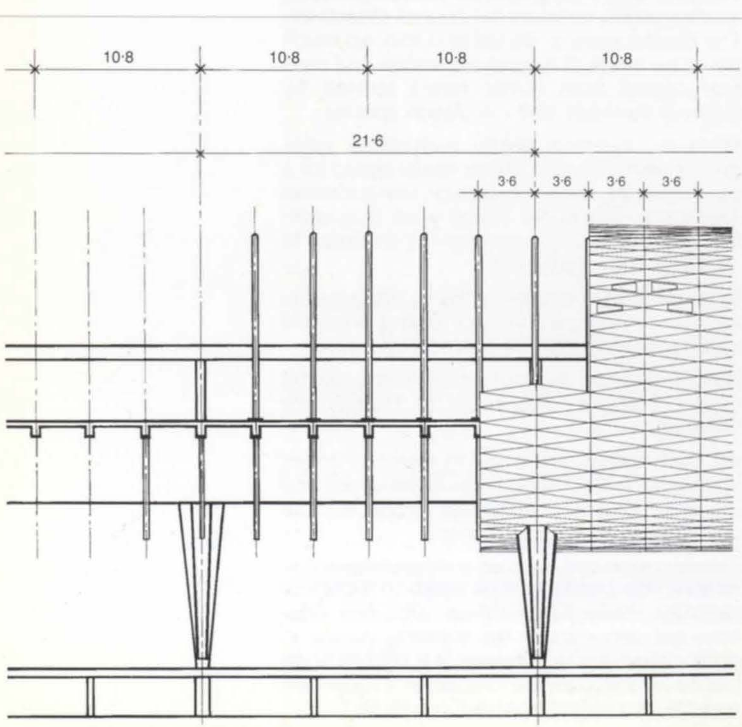
Though perceived as a piece of visionary architecture, the building owes much to technical rationale. Some of the issues and their solutions are described in the following pages; in such a short space, however, it is difficult to do justice to the plethora of design challenges and the processes involved in solving them.



2.
Site plan.
1-4 Administratif
1 Block A
2 Atrium
3 Ovoid within Atrium
4 Block B with Aerofil above
5 Deliberatif



3.
Administratif structural diagram.



4.
Deliberatif structural diagram.

The site

The building as a whole was conceived in section, leading to an extruded form by virtue of the section being repeated and so becoming a linear building. When such a linear form is superimposed on the site a number of fundamental design issues arise. The northern one-third of the site is traversed obliquely by the St. Just metro station; roughly orientated south-west to north-east and semi-buried as it was, the metro had to be built over to accommodate a linear building. It was accepted that transfer structures would be required and that these would play a fundamental role in how the building was organized. The metro continues its journey south below ground and the tunnel forms the site's western boundary. Again, this gave clues as to how the building might be arranged, if overly complex foundations were to be avoided.

The eastern and southern boundaries are bordered by highways raised 6-8m above a generally flat site. Their retaining structures made it preferable to keep them as they were, which in turn implied that a new perimeter road might act as separation between new and old, again avoiding awkward foundations.

The geography and geometry of the site, as always, gave clues as to how any development might function. Predominant winds, for example, accelerate through and above valleys and hills to the north, arriving over suburban terrain as the mistral. Potentially both friend and foe, the wind effects obviously required careful study, but if well understood might be used to advantage. In terms of climate, therefore, the approximately north-south major axis of the site presented design opportunities. An east-west axis naturally prompted consideration of sun-path and light intensity. Although the site was flanked by the eastern highway, there was little natural shading; furthermore, traffic noise would require special consideration, the highways being close to any future building. A considerable area of flat land to the west was to be developed; here, significantly tall buildings could affect late evening sun, as well as prevailing west winds. It was accepted that the impact of such development should be reviewed retrospectively once plans were published. Later in the design development, two options for this land were defined and incorporated into the wind model testing.

Geological conditions did not influence the building form at all. Sandstone, the major founding material, would carry load well, and the *remblais* – granular material and river deposits above this, some 5m deep – were found to be dry and only requiring simple excavation techniques. Fine river deposits and the former course of the River Jarret explained the presence of a large culvert, installed to direct storm water from the northern area of the city. Evidence suggested that a dry basement could be constructed and traditional piles or barrettes used.

Modular order

Although it is not immediately obvious, a module of rich order – not competing with the more liberal volumes and surfaces – underlies the building's arrangement. Its origin is in the office planning grid of 5.4m; by doubling this to 10.8m in the basement, using an X-column arrangement of transfer structures, four car parking spaces and a column zone are achieved. By again doubling to 21.6m, the main structural grid of the Deliberatif is defined, and then a division of this yields six 3.6m panels of cladding between major grids. In turn, this links well with the geometric theme of the Deliberatif envelope and practical considerations of panel manufacture. Furthermore, the lowest common dimension of 300mm permits a neat transition between large-scale structure and smaller elements of construction within the building.

The Administratif

Some parts of the total project are complex, not from technical vanity or design exuberance, but from the defence of ordered rationale that allows the vast majority of it to be realised with great economy. Protection of this higher order simplicity yields pockets of complexity – the consequence, primarily, of the way several simple elements interact. The Administratif, though, is a large but generally simple concrete building, housing amenities and consolidated office space for the Département. These are located in the two blocks, separated by the continuous Atrium throughout their 150m length. For ease of reference the lower block and most westerly is Block A. The higher, Block B, also carries the Aerofoil building above terrace level, whilst the Atrium houses a free-standing structure, the Ovoid. These five elements, Blocks A and B, the Aerofoil, the Ovoid, and the Atrium constitute the Administratif.

Despite their geometric differences, Blocks A and B are constructed identically. Common to both, and perhaps the key reference point, is level 1, approximately 12m above the arrival floor and the level at which the X-columns commence their work. The in situ concrete floors above are supported by four in situ/precast columns, making three spans laterally. The centre span, and that most penetrated by services, uses *pré-dalles,* a form of concrete permanent shuttering not dissimilar to the *Omnia* system. Longitudinally, the columns are on the 5.4m grid, which balances well with the glazing module, partitioning and preferred office module. The columns on the perimeter have an elliptical section with two continuous slots for fixing partitions.

The central, longitudinal beams were cast using a module of penetrations through the web to allow free passage of services. The system of beams and slab permitted the contractor to standardize and use rolling shutters for the two outer spans.

Each block is stabilized against horizontal load by four cores, cantilevering over 90m from foundation level, arranged around escape stairs at approximately 32m intervals. There are expansion joints at each end of the central 50m length, continuous throughout the height of the building. A system of bayonet joints prevent excessive torsion in the two outer cores. The stability system and X-columns interact longitudinally due to the high shear stiffness of columns below level 1.

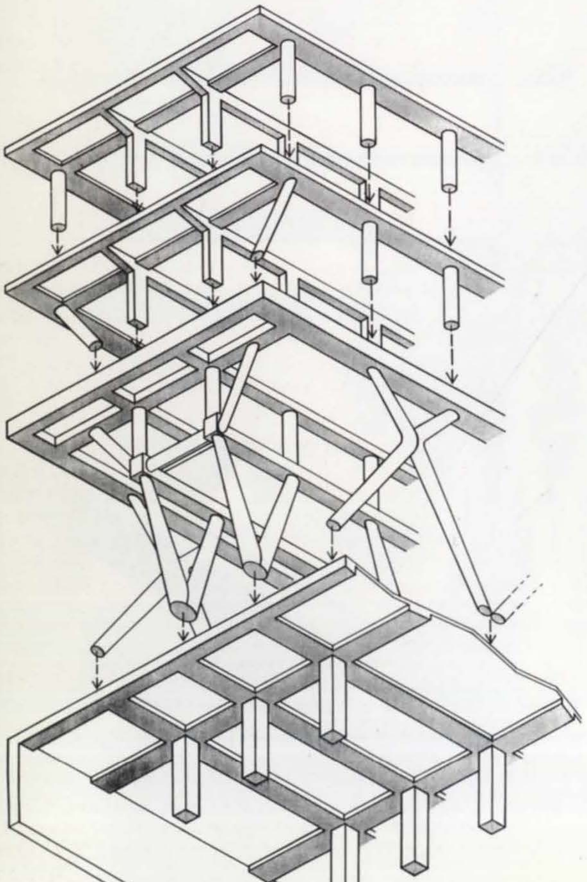
In the basement, it was decided to avoid expensive and cumbersome transfer beams and exploit instead the geometry of expressed structure. The X-columns at level 1 allowed an elegant transfer of load from 5.4m to 10.8m over three storeys, from the perimeter columns of the offices above. A series of V-columns, commencing at lower mezzanine level, transfer load over one storey from the internal columns to those below.

Tapering in section, the X-columns were cast in situ using four specially fabricated steel shutters, two each for Blocks A and B. These arrived on site in four pieces, complete with rolling gantry and jig. Access points at three levels allowed concrete to be poured and compacted in three stages: from reinforcement cage construction to finished column took 2.5 days. The somewhat smaller V-columns are of precast concrete with an in situ stitch at the lower knuckle, cast in a specially fabricated steel shutter. The two elements of the V were stabilized by temporary frames until the tie was made at mezzanine level.

The gable frame

The *ossature du pignon* is very much a three-dimensional concrete structure. It gathers load from the external columns by a series of inclined struts and ties and transfers it back to the internal V-columns below mezzanine, at the same time turning the forces through 90° on plan. All this both protects the extruded form of the Administratif and articulates the structure within the building. Clarity of line and the simplicity of the X-columns is, then, all that remains externally despite the apparent cantilever of 7.5m beyond the last X. This feature is further emphasized by the glazing, deliberately set behind the X-columns to leave their form exposed.

5.
Detail of the Ovoid within the Atrium.



6.

6.
Administratif gable end structural diagram.

7.
Gable under construction, January 1993.

The Aerofoil

The Aerofoil continues Block B's four-column arrangement upward, though the blade-like precast external pilotis which elevate it have their own character.

They vary in section with height, a circle of small diameter at the base transforming to a long ellipse at their head. This form suggests a portal structure for stability, but this is not the case; the Aerofoil takes its stability from cores, like the rest of Block B.

In section the Aerofoil has a curved profile, framed in structural steelwork bent to differing radii, and arranged as a series of frames at 5.4m centres. Each frame, stable in its own right, is bolted to the main concrete floors.The Aerofoil includes two floors, levels 8 and 9, and houses the presidential suite. It also allows commanding views over Marseille and to the sea beyond.

The Atrium

The Atrium is not only the cathedral-scale dividing element between Blocks A and B, but also a piece of 'machinery' which actively moderates its internal climate. This is in part achieved by static measures like roof and gable glazing, but also actively via programmed sensors on the roof that track the sun and measure wind velocity.

These enable maximum benefit to be derived from natural phenomena, controlling and adjusting shutters and blinds in response to changing conditions and climate.

As with all large glazed spaces, the Atrium can experience violent swings and steep gradients of temperature. Due mainly to the sheer volume of the space, it is difficult to control the internal environment as a whole. Those areas subject to frequent human occupation were considered and addressed on the basis of local control. Two major areas were identified: the bridges (*passerelles*) which traverse the Atrium (two groups on four levels) and the Atrium floor.

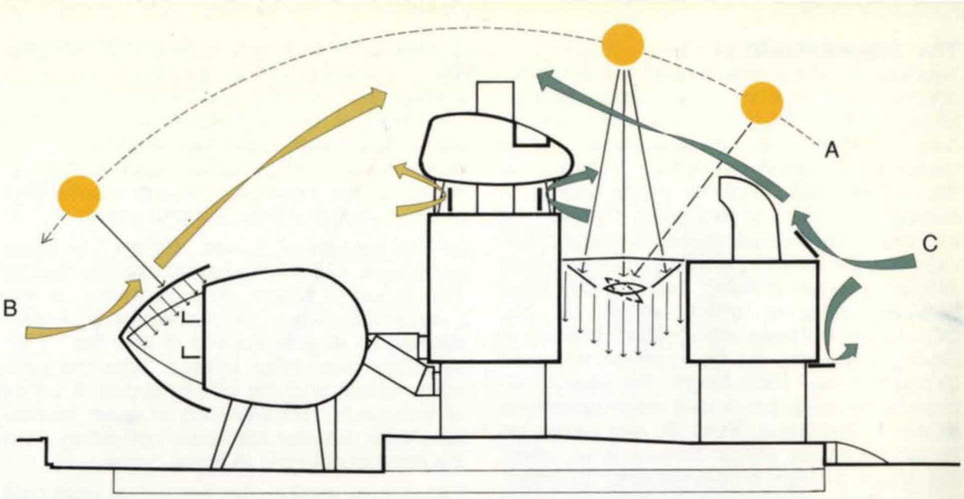
Laid within the screed of the latter (*rez-de-chaussée*) is a network of pipes for underfloor heating. Radiated heat from these warms the lower reaches of the Atrium in winter, whilst in summer a secondary cooling circuit, using the same pipework, provides a radiant cooling effect from the slab.

Cooling is supplied from the central chiller plant. Serving the whole building, this comprises three 1152kW units and one 562kW, the latter handling equipment loads from the Administratif in winter.

The bridges link Blocks A and B across the Atrium at each level. Elevated as they are, they can experience large temperature variations due to stratification of air in summer and cold draughts in winter. Rather than be left exposed, each bridge is partially enclosed and has an electric underfloor heating system.

The Atrium roof is at the highest level of Block A and spans 18m to level 5 on Block B; these highest office levels in each Block need protection from solar gain. This is achieved in two ways: by static, raked, tensile screens attached to each roof truss; and by a central solar paddle whose angle is moved in response to the sun's position by a computer to give maximum shading.

The system is in turn linked to a Building Management System (BMS).The Atrium ventilation and smoke extract system relies completely on natural means. More sensors on the roof relay wind velocity to the BMS. Vents on the roof open and close in response to the wind-induced pressure distribution, controlling the intake and exit of air. In the event of fire the solar paddles are rotated to the vertical position to give maximum area for smoke dissipation. The automatic venting control can be over-ridden and manually controlled by firemen from the fire control panel.



A : Sun path • Shading
B : Sirocco • Wind protection
C : Mistral • Wind protection

8.
Response of building form to specific environmental criteria.

9.
End elevation, showing from left to right: Deliberatif, Administratif Block B with Aerofoil above, the Atrium, Administratif Block A.

◀10.
The Atrium.

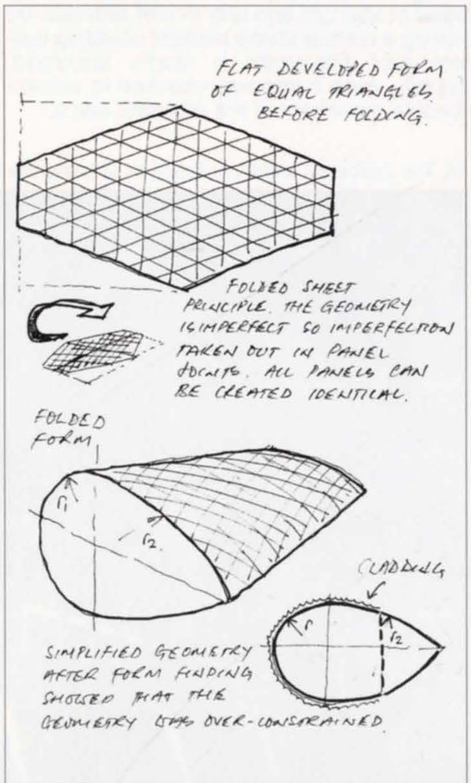
The structural efficiency of the roof truss section and the overall geometry are in harmony with the shading system. Two-point funicular trusses, arranged to match the 5.4m grid, have a dual function. The top boom carries the glazing and window cleaning equipment, whilst the three-part bottom boom has outer elements supporting fabric shades and a centre portion supporting the axle of the solar paddle. In making the solar paddles aerofoil-shaped and then mirroring this in the bottom boom, local bending is resolved by the axle taking its support at position of greatest depth.

Just as the Administratif Blocks are broken by movement joints, so is its roof. Potential stresses are relieved by sliding joints in the longitudinal members and strategically placed horizontal bracing. Lateral and independent movement of Blocks A and B is possible by fixing roof trusses to the former and using a guided bearing on Block B, the opposite side. Fabricated steel mountings terminate circular hollow sections which make up the principal elements of each truss.

Gable glazing

Given that lateral movement between the Blocks could be significant and that the gable glazing should fill the gap between Blocks A and B, the roof, and the floor, it was decided very early that the glazing should be suspended. A system of jibs (similar to cranes) were designed as part of the roof structure. At roof level they have cables attached, each taking vertical load and preventing twist in the horizontal wind girders, which give lateral stiffness to the glazing and double as cleaning platforms. Due to possible differential horizontal movement between A and B, each girder sits in sliding bearings at each floor level. A and B can then move independently, with the glass suspended between, and only longitudinal forces from wind transferred to them. Differential longitudinal movement between each Block is not significant and a system of flexible gaskets form a resilient seal to the glass and buildings.

It was predicted that the cables may loosen under certain loads. To prevent this, the whole structure was pre-loaded during erection, creating prestress in the cables and thus controlling loss of tension.



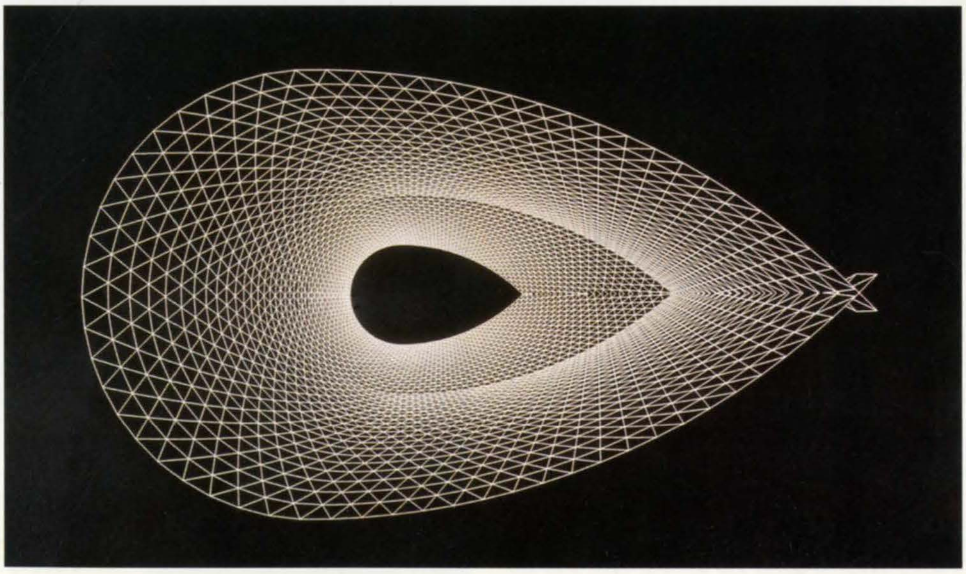
The Deliberatif
A study in form

The Deliberatif has a distinctive aerofoil-like cross-section that serves to smooth out east-west wind flow, its shape the product of a geometric study aimed to create a surface where each cladding panel is identical. The structure, rather than being pre-defined, would respond to panel size and section geometry.

The catalyst was an exercise in paper folding. By scoring isosceles triangles onto a rectangular piece of card, cropping the corners to create a symmetrical coffin-like shape, and then folding into a wing profile, a geometric starting-point was defined. This exercise suggested that each panel could be similar. Form-finding techniques, similar to those used in membrane structures, demonstrated that extending this philosophy beyond 12 triangular panels would create distortion in them. Furthermore, the accommodation to be created inside the Deliberatif, as well as practical considerations in panel production, dictated that a larger number of small panels should be used. The distortion therefore had to be quantified and further tested.

◀11.
Developing the Deliberatif geometric form.

▼12.
Computer image of Deliberatif geometric form.



By simplifying the cross-section, using two superimposed circles and varying the radii to follow the folded paper concept, it was possible to quantify panel distortion – or, equally, retain each panel identical and calculate distortion in the joints.

The latter concept was tested against a maximum panel size of 3-4m, enclosing a volume derived from planning the internal space required. The results of computer drawings and mathematics revealed that distortions could be readily absorbed by joints no wider than 25mm using a flat triangular panel of 3.6m x 1m. The trailing edge, however, contained much greater imperfection and would require special panels or a closing strip.

Accepting distortion allowed the building envelope to be developed and the overall concept to proceed.

The building

The Deliberatif is physically separated from the Administratif, from which it can only be reached by escalator, stair or high level walkway. There is separate lift access, for restricted use, from the car-park. It contains the major debating chamber, public galleries, reception halls and functional suites – very much a public space and a focal point of the design. The building is readily divisible into two major elements: a concrete platform 8-10m above the floor of arrival, and the aerofoil-like structure wrapping around it.

Although some 160m in length, it was decided to build the concrete frame without movement joints (contrary to common French practice). This would help create the continuous shell-like cladding, an important feature of the design. By careful understanding and manipulation of stress levels, it was possible to estimate shrinkage forces and design the structural elements accordingly.

The concrete platform is supported on 16 columns, arranged in pairs, and spaced at 21.6m. Each tapers with height and is based on a cropped triangular section at its head (approximately 3 x 3m). The section subtly changes to a flattened hexagon at its base (approximately 1.5 x 1m). Specially designed steel gantries allowed each pair of columns to be cast in one operation.

All the columns are linked by storey-height concrete beams which complete portal frames for lateral and longitudinal loads. At the most northerly frame, the western leg kicks out at 45° to permit the metro line to pass below.

Generally, however, the western columns are vertical and those to the east inclined. Due to shrinkage of the structure, bending forces in the columns and beams were minimized by constructing from each end, leaving the central zone free until much of the movement had taken place. Thermal effects are less significant, since the concrete frame is largely enclosed.

Accommodation is arranged on three floors, the lower two which house plant and storage being continuous throughout the length.

The upper floor is intermittently omitted to allow large double-height volumes for the debating chambers.

Surrounding the accommodation is a shell-like outer skin of triangular metal cladding panels. The weather seal lies beneath and consists of a membrane laid over plywood panels of similar geometry to the metal ones above. Insulation and vapour barriers lie beneath the plywood panels on separate chassis, again of the same triangular geometry.

Panels are 3.6m long, supported at each corner by the main, steel annular frames. This steel structure follows the aerofoil section.

Each steel frame is bent to a specific radius, particular to that grid line and one other on the opposite side of the centre line. Circular hollow sections form a continuous element that totally encloses the concrete frame. Over the majority of the surface the section is reinforced by welding on a T-section. This also serves as a surface to attach cladding. At the sharp edge the T is omitted and a lattice frame controls both strength and deflection. This is exposed and free of cladding panels, instead carrying two levels of walkways and giving support to a stretched membrane structure. The fabric membrane (PTFE-coated) extends for 21.6m on the exposed, central, bay of the building. A network of stays and cables translates imparted force back to the principal frame.

Conveniently located behind the membrane structure is the longitudinal stability system for the steel rings. As elsewhere, lateral forces are carried by the concrete frame to which rings are attached around their perimeter.

The steel frame responds to expansion and contraction by through central braced bays. Where steelwork is exposed, longitudinal elements are omitted at intervals to allow greater freedom of movement.

Each steel ring was pre-cambered to compensate for the deflection that occurs when all permanent elements are installed. By so doing the structure was designed on the basis of strength and only in part stiffness. By having a comparatively resilient cladding system such movement is readily absorbed. Equally, each frame was checked to accommodate movement of the concrete frame.

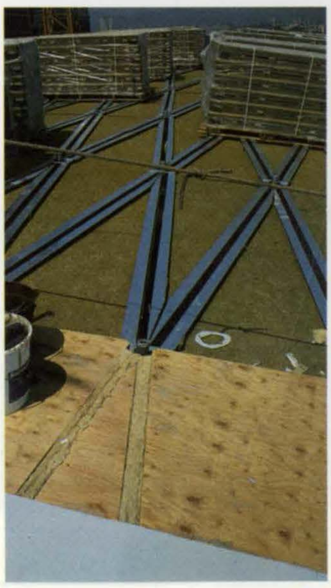
At the southern end of the Deliberatif is the 'aviary' walkway, its name a legacy of earlier proposals. This element cantilevers 12m from the concrete structure, and consists of an extruded circular section fabricated in tubular steel and pre-tensioned against movement. It is clad in glass whose blue tint varies in density as it progresses away from the building. The end panels are clear.

Climate control within the Deliberatif is achieved by conventional means. Chillers and boiler plant are remote from the building and part of the central system. Major public spaces and debating chambers are served by dedicated all-air systems. Predicted occupancy levels of the major spaces can vary considerably. Consequently the ratio of fresh air to re-circulated air is pre-programmed, continually modulated by the central control systems to meet demand.

Special attention was paid to designing a system that meets stringently low noise levels. This required the selection of high performance grilles and attenuators. Ductwork was also sized for low velocity air-flow so that noise is not regenerated within the system. Function suites, bars, library, and offices are served by four pipe fan coils to condition the space, each being fed from central plant.

By introducing a stretched fabric structure to the eastern exposed side, the walkways are shaded. Furthermore, solar gain is controlled for those areas immediately behind, which are enclosed by a large glass screen.

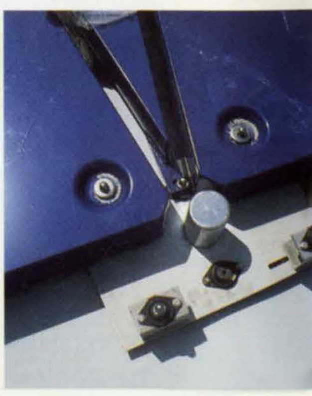
13. The Deliberatif under construction, showing the concrete platform.



◀15.
Metal cladding panels being laid over the white membrane.

◀14. Layers of Deliberatif roof; top: insulation and vapour barriers in steel frame; middle: plywood panels; bottom: weather seal membrane (white).

16.
Metal cladding panels with support detail.



◀ 17.
End view of transfer beam over metro station.

18. ▶
The Marseille context, viewed from the north east; behind the Hôtel is the Salle de Rock, a new community facility; in the foreground, a deep car park to serve both buildings.

Basement transfer structure foundations

The basement covers an area equivalent to five football pitches. Arranged on two levels, it shelters plantrooms, kitchens, workshops and technical facilities, as well as the car parking spaces. To the north there are nine major transfer beams, spanning up to 30m and supporting the full weight of the buildings above. Built around and through these beams is St Just metro station. Below them passes the twin metro tracks and platforms. The transfer beams were cast in situ some 0.5m above their final position over the railway, and then lowered by jacks to their final resting position. The contractor chose to prestress the transfer beams, done in three phases to avoid temporary over-stress of the concrete.

By carefully co-ordinating the time at which stressing could occur and relating this to the construction above, an economic and not excessively deep transfer system was achieved. The overall depth of beams varies between 3.0 and 4.2m to follow the gradient of the railway below.

Between each transfer beam are either plantrooms or access to the metro station. To the east the core of Block A rises above. Given that the station traversed the full width of building, it was possible to arrange the stability so that only one core (the shortest and lightest) sat over the railway. The rhythm of the buildings above was therefore undisturbed and an economy of scale achieved.

The foundations are of two principal types: barrettes, constructed as mini diaphragm walls, and more conventional bored piles. Barrettes allow the designer great scope to create various geometric plan forms made up from a rectangular block shape. H, I, T, X and other shapes can be constructed to reflect the most efficient medium for retaining loads imposed on them. This opportunity was exploited to the full beneath the Deliberatif, where the foundations are subject to considerable lateral load – due to geometry, and to shrinkage and thermal effects from the structure above.

Although traditional piling is used, the piles were installed using an interesting technique called the *Starsol* system. While the bored piles were being installed, ground strength was monitored continually by measuring boring resistance, monitored directly by a computer in the cab of the machine.

Comparison to the design parameters then permitted the pile to be terminated once the required level of resistance had been reached. Barrettes are generally used where high bending or shear forces exist and piles take primarily vertical load.

Wind study

The design team suspected that French regulations provided an overly simplistic measure of wind effects. Statistical data on wind speed and direction were therefore gathered from the local airport and used in a separate analysis using recent work by the Engineering Sciences Data Unit.

This related ground roughness and local geography to judge wind speed as a function of direction, so achieving a more realistic set of conditions to assess the building section. Once complete, the analysis could be used in wind tunnel tests. These were commissioned and carried out by Bristol University. The object was to understand the pattern of wind flow, so as to judge the effectiveness of passive ventilation and the local effects around the base of the building. It would also serve to govern the strategy for locating wind deflectors which would manage flow.

A rotating table was used for scale model tests, which allowed varying directions to be assessed.

The wind studies also modelled the effect on the building of two different options for future development on the adjacent, vacant site to the west. The study enabled the most effective position of vents to be chosen and provided pressure contours around the Atrium.

Furthermore, although not modelled for this purpose, some knowledge was gained of local pressures around the Deliberatif structure.

People

The building was completed within budget in October 1994 and is now fully occupied. Architecture is about creating buildings, but it is also about people: people who design, people who build, people who use, people who observe, people who comment. A task on this scale touches many hundreds, all of whom contribute in their own way to the creation of something enormous, complex, and unique.

Credits

Client:
Conseil Général des Bouches-du-Rhône

Architect:
William Alsop Architects

Consulting engineers:
Ove Arup & Partners: Pierre Balosso, Mike Banfi, Peter Chapman, Marcial Echenique, Martin Fenn, Brian Forster, Alistair Hughes, Colin Jackson, Chris Judd, Man Kang, Bob Lang, Ruth Lees, Joanna Massey, Chris McCarthy, Hugh Muirhead , Maurice Mullaly, Dominic Munro, Neil Noble, John Pilkington, Ian Smith, Jean-Paul Velon (structural)
David Anderson, Sean Billings (façades)
John Ducke, C W Li, Paul Pompili, Manan Shah, Mike Summers (electrical)
Guy Battle, Alan Burfoot, Lee Carter, Phil Connor, Colin Darlington, Alan Foster, Clodâgh Ryan, Martin Walton (mechanical)
Jonathan Ward, Terry Watson (public health)
Rachel Kelly, Alain Marcetteau, Howard Roscoe (geotechnical)
Colin English (acoustics)
Andrew Allsop (wind studies)
Terence Haslett (computing)
Ghislaine Frayssignes (administration)

Project manager:
SCIC-AMO/G3A

Quantity surveyor:
Hanscomb Ltd.

Engineering sub-consultant:
OTH Méditerranée

Concrete structure contractor:
MCB/CBC

Deliberatif cladding contractor:
Cabrol

Mechanical contractor:
Albouy/AIC/TNEE

Electrical contractor:
Cegelec/EI/SNVD/CIREM

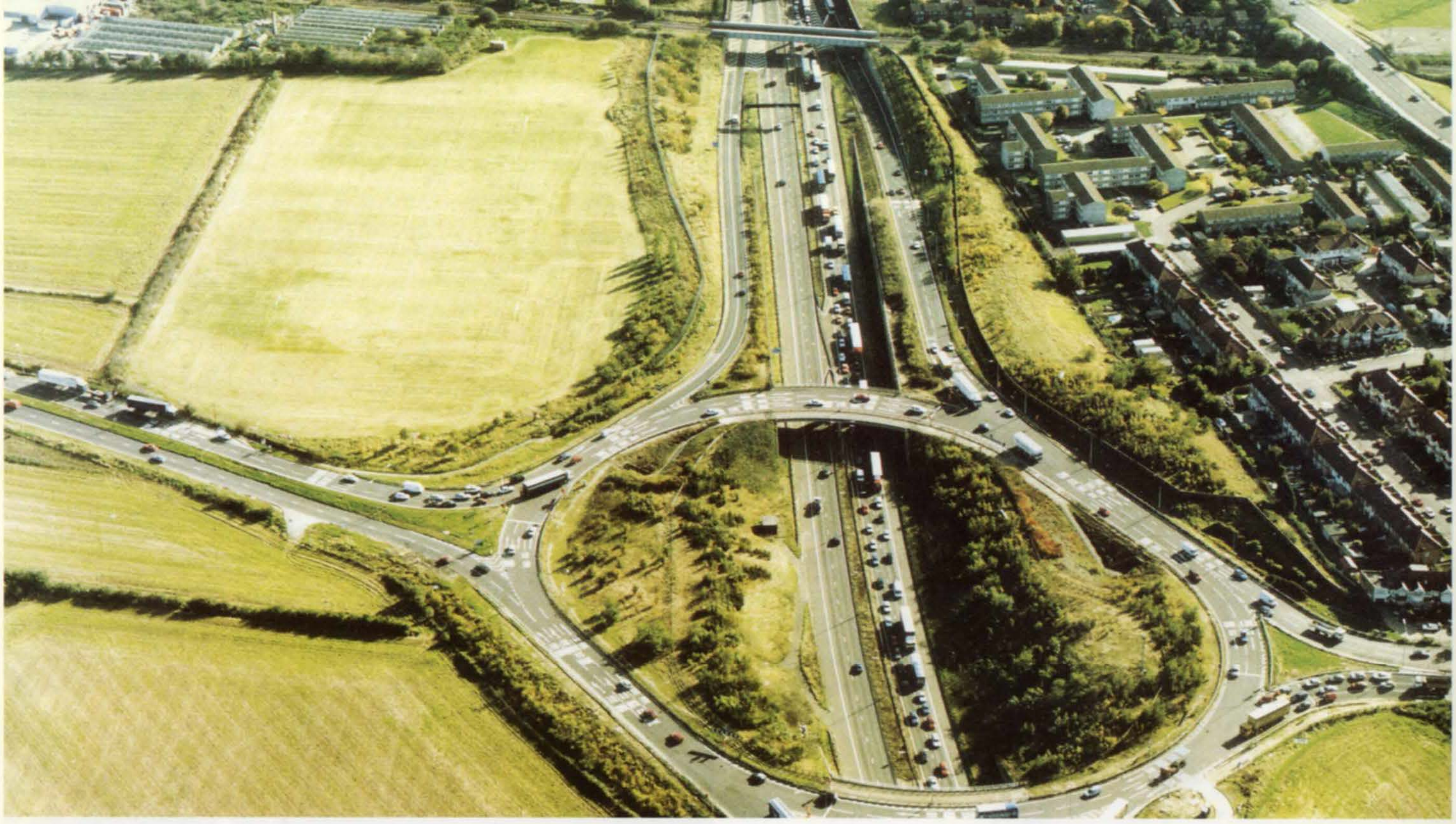
Lifts contractor:
Otis Elevator Co.

Foundations:
Soletanche

Fire security consultant:
Casso Gaudin

Kitchen consultant:
Jolyon Drury

Illustrations:
1, 5, 9, 13: Paul Rafferty; 2: Denis Kirtley; 3-4, 6, 8, 17: William Alsop Architects; 7, 14-16: Hugh Muirhead; 10: John Edward Linden; 11: Bob Lang; 12: Ove Arup & Partners; 18: Cerf Blanc



Motorway widening projects

Phil Hall

1. Congestion on the westbound carriageway of the M25 at Junction 25 with the A10.

Introduction

In its 1989 White Paper entitled 'Roads for Prosperity', the Government announced a major programme of motorway widening, the implementation of which presented a huge range of engineering and environmental challenges. Arups' experience over the years on major highway schemes, as well as their expertise in option studies and economic and environmental assessments, made the firm well-placed to win a major share of the work, particularly as the Department of Transport (DoT) had set up its own Motorway Widening Unit (MWU) within 5km of the principal Arup office concerned with highway and bridge design.

Widening studies

One of the Government's very early feasibility studies looked at the whole 290km length of the M1 motorway from London to Leeds. Arups were awarded this study, which provided the ground rules for much subsequent work, and were also appointed by the MWU to join a Motorway Widening Steering Group of leading DoT specialists in particular aspects of scheme evaluation. Arups' contribution to this 'think-tank' also extended their capability in the field of widening.

Following these two initiatives the firm has been appointed for four major widening studies (three from the MWU and one from the DoT's Eastern Regional Office, who handle part of the M25) (Fig.2).

2. The motorway network and current widening programme.

The current projects are:

- M1 Junctions 15 to 19 (35km)
- M6 Junctions 11 to 16 (53km)
- M25 Junctions 23 to 28 (40km)
- M42 Junctions 1 to 7 (34 km).

In addition, the Cardiff office are examining a new route for the section of the M4 which at present passes through north Newport. This new route would provide a direct link from Cardiff to the Second Severn Crossing, now under construction.

Key factors in widening

The basis of the 'need' to widen motorways is quite simply the sheer pressure of traffic demand (Fig.1), both now and into the future, but a comprehensive response to this requires the deployment of a wide range of skills, preferably within one organization.

Traffic forecasting

Whether this is seen as an art or a science, certain skilled forecasting procedures have to be followed to predict future traffic levels. Arups have developed extensive and detailed mathematical traffic models using geographical information to delineate road networks, and data on travel patterns gained from surveys designed and supervised in-house.

These surveys, consisting of roadside interviews with drivers, clarify traffic demands; traffic modelling for the M6 scheme, for example, used data from interviews covering the area from Oxford to Liverpool and Manchester. These forecasting procedures have been consistent with national prediction methods, but the models also reflect the specific circumstances of the scheme being developed. For example, major development projects such as the expansion of the National Exhibition Centre near Birmingham have been incorporated to identify local effects at nearby junctions.

The prediction techniques required to forecast traffic may require months of painstaking effort and major computing exercises. Transport modelling and traffic engineering skills have been used to understand the consequences of margins of uncertainty in these forecasts on the need for the scheme and the scale of the proposed widening. This transportation planning advice is crucial in guiding highway engineers so that safe and satisfactory road and junction layouts can be designed. The elements of uncertainty also impinge on the work of Arup Acoustics and Arup Environmental, who use this traffic data for several types of environmental assessment (e.g. noise and air quality issues) which are the subject of national debate.

Economic justification

Motorway widening schemes require large amounts of public expenditure, typically from £3M-£7M/km. The majority of the work on the justification of schemes has been undertaken using relatively standardized DoT procedures, but it has become normal practice to extrapolate the computer programs used beyond their normal parameters. Arups have developed novel approaches to economic justification, and have prepared discussion papers for the DoT to help resolve the emerging issues.

The economic benefits of widening have been determined using the two programs COBA and QUADRO to evaluate savings in drivers' time, accidents, and vehicle operating costs. The major consideration in widening schemes is the immense disruption which may have to be faced during construction, and the reduction of this disruption is a major influence on the form of widening, and the choice between options. Delays during future road maintenance operations have also been calculated, in order to establish the ability of a widened motorway to handle traffic more readily.

Methods of widening

'Rapid' widening

Pressure of existing traffic on London's M25 Orbital Motorway led the DoT to seek, for the section from South Mimms in Hertfordshire to Brentwood, Essex, a widening method capable of quick implementation; development of the 'rapid' technique (Fig.3) was the outcome.

Its key feature is that it will be carried out entirely within the existing fence lines, with no land acquisition. Existing bridges will be retained and much of the carriageway re-used. It will therefore be quick to build, at least in the sense that no land acquisition procedures are needed. The adverse aspect of 'rapid' widening is that traffic disruption may be intense, and it is therefore necessary to develop traffic management layouts which help to ensure the safety of both the motorist and of the workforce. Experience gained on the new motorway construction of the '70s and '80s was very relevant, since much of this work necessitated new construction adjacent to or connecting with existing motorways. The scope for environmental enhancement is limited, however, since no land is available outside the present boundary.

Nevertheless, the 'rapid' technique still requires the full range of engineering investigation and design, particularly in relation to geotechnical issues and the design of retaining structures, areas where a sensitive approach is needed in difficult locations.

Parallel widening

For the most heavily trafficked routes, and where land is more readily available, alternative widening techniques have been examined. Three major options have been extensively studied and compared in terms of disruption, safety, costing and environmental issues. For symmetrical widening, new lanes are provided on the outside of each carriageway. For asymmetrical widening, one boundary remains and the widening is concentrated on the other. However, the third option is increasingly favoured, and this is called 'parallel' widening. Fig.4 shows the construction stages.

Arups have devoted a major effort to looking at alternative forms of parallel widening, and have made comprehensive recommendations to the MWU. This report concluded that the technique provides considerable flexibility to avoid sensitive features, and that even small changes in position can have major benefits in terms of drainage, structural demolition and construction, and both worker and driver safety.

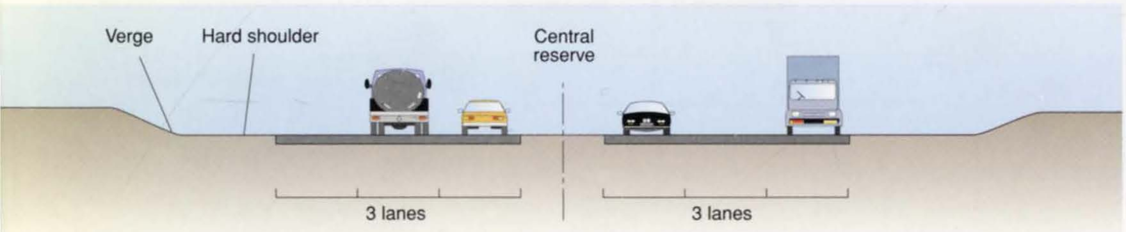
Work on developing the 'parallel' form of widening has established that the layout takes longer to build, and the need for land means longer lead-in times. All existing structures need to be replaced or extended, and most of the existing carriageway and drainage has to be renewed. The landtake is also greater. However there are major opportunities to incorporate substantial landscape and acoustic measures, existing traffic is barely disrupted, and safety for construction workers is greatly enhanced.

Junction design

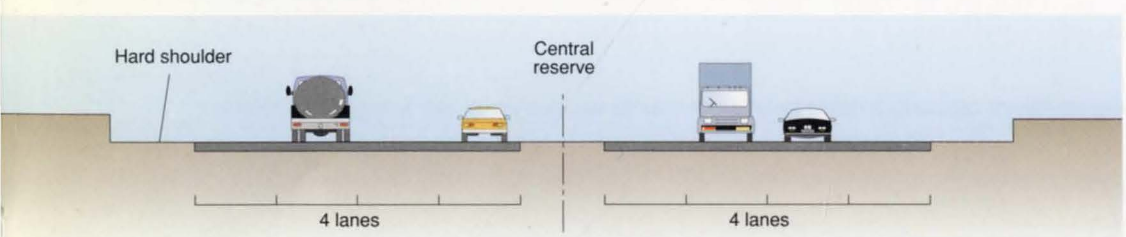
The forecast levels of traffic have caused major problems for the highway engineer in designing junctions which are adequate in terms of capacity and safety, but which are sensible and reasonable in terms of landtake and impact (Fig.5).

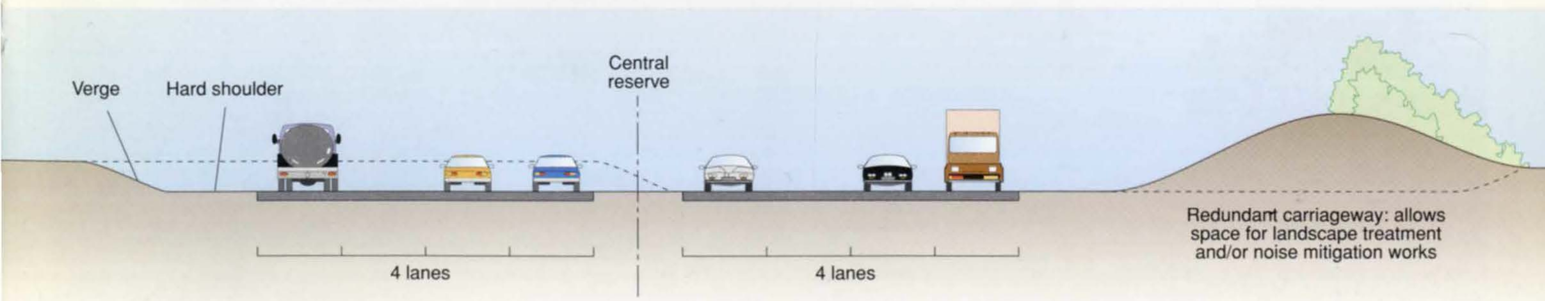
The problem has been particularly acute on the M42 widening, since this serves as an orbital route around south and east Birmingham. It is heavily used by relatively local traffic, which uses junctions to 'hop' from one radial route to another. Increasing use is likely to be made of complex, traffic signal-controlled junctions, with some traffic movements segregated. In the vicinity of the National Exhibition Centre, additional links need to be provided to meet the massive traffic problem experienced on major show days. A more general problem which has been addressed is the need to develop traffic models which are increasingly sensitive to peak period travel demands and the ability of the road network to sustain growth. Detailed discussions about the future traffic modelling techniques are under way with the DoT, to ensure that junction designs for peak hours are compatible with the capacity of the rest of the network.

5. Model of new junction layout designed by Arups on the M6.



3. Above: existing dual three-lane motorway; below: symmetrical widening without land take (rapid widening).

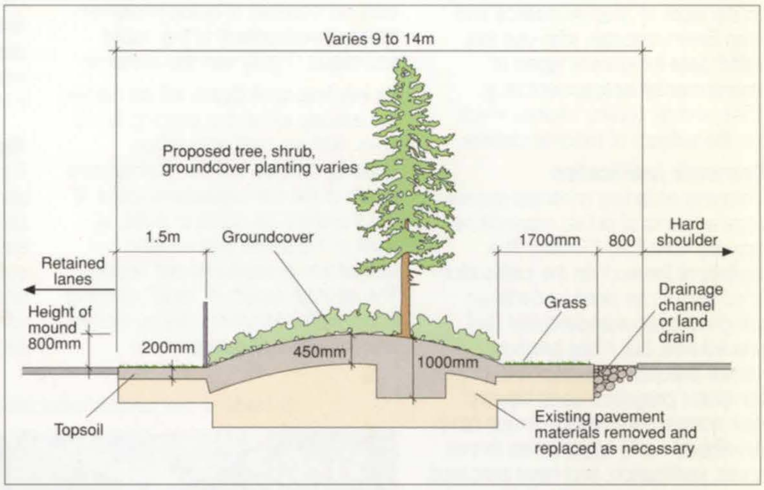




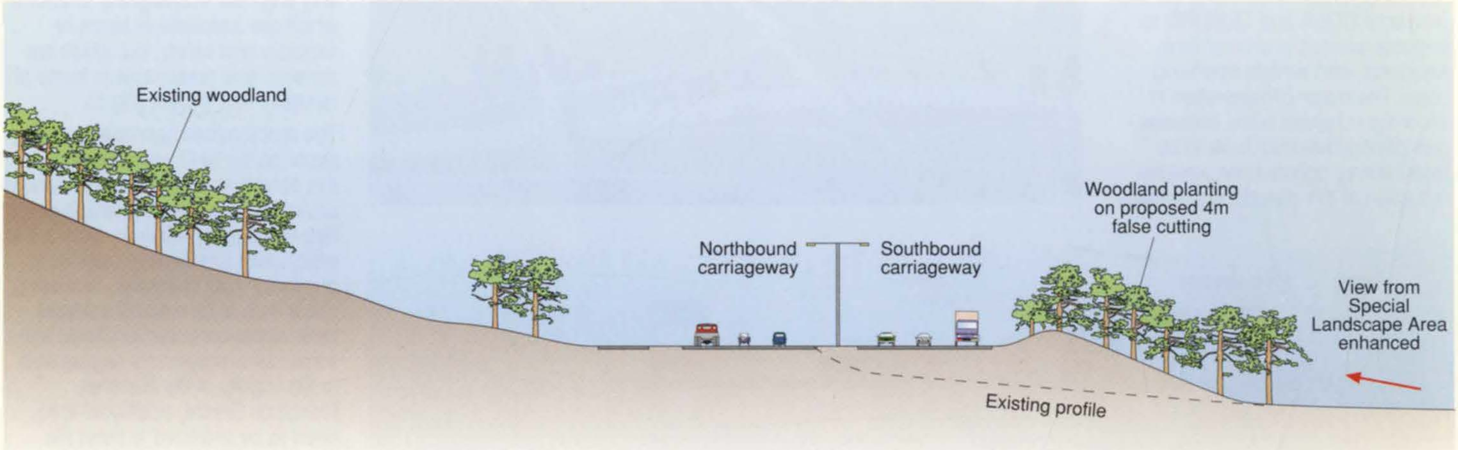
4. Parallel widening.

Landscape
Tom Armour

While a widened motorway remains a narrow strip, its effects on the landscape can nevertheless extend over a wide area. Over the length of the scheme, a variety of landscape forms are likely to be encountered – from rolling countryside, through open, agricultural land, to urban and suburban fringe areas – and consequently a variety of design approaches are required. Each type of landscape needs detailed assessment and consideration of its cultural, historical, and amenity value. Arups' own landscape architects advised the engineers and client on appropriate treatments and detailing, and inform the project team of the potential impacts, benefits and disbenefits of widening alternatives and the best way forward in landscape terms. As with all environmental considerations, environmental design is an integral part of the overall engineering design. The aim is for the scheme to be designed in the context of the environmental setting, rather than needing add-on mitigation measures in response to adverse effects. Arup Environmental also have an important role in advising on the aesthetic implications of motorway structures, bridges, retaining walls, noise barriers, etc. Considerable liaison has been achieved between the landscape architect, the traffic noise specialist, the ecologist, and the engineer.

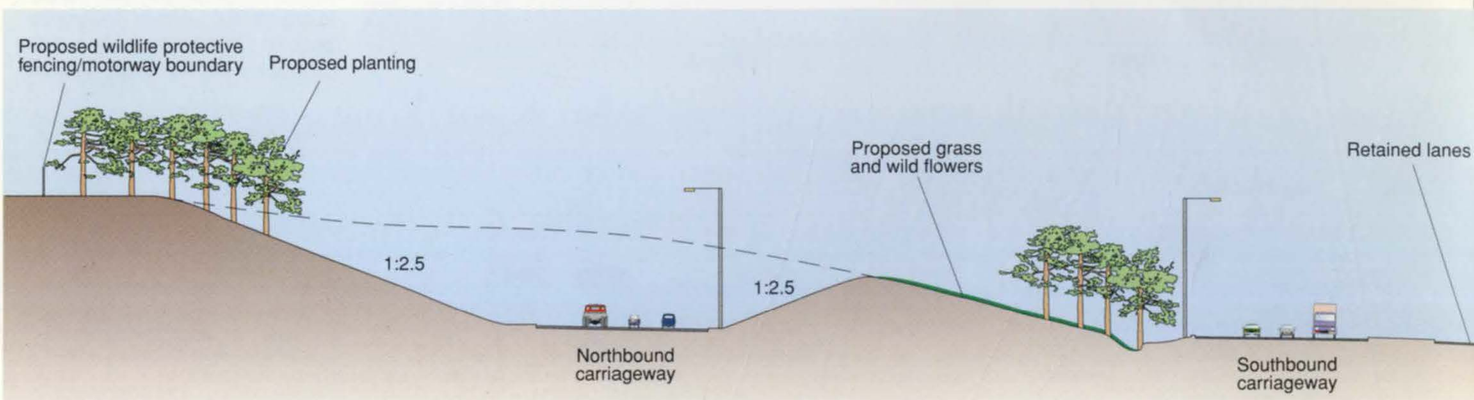


6. Existing location on the M6, and right: 7. Landscape treatment of widened median: these were introduced to reduce the apparent extent of road surface.



8. Proposed scheme for widening on the M6 (see Fig.6): it provides the opportunity to create a false cutting to screen traffic and enhance features within a Special Landscape Area.

9. Splitting the carriageway provides the opportunity to reduce the impact for motorists and visual impact from the surrounding landscape.

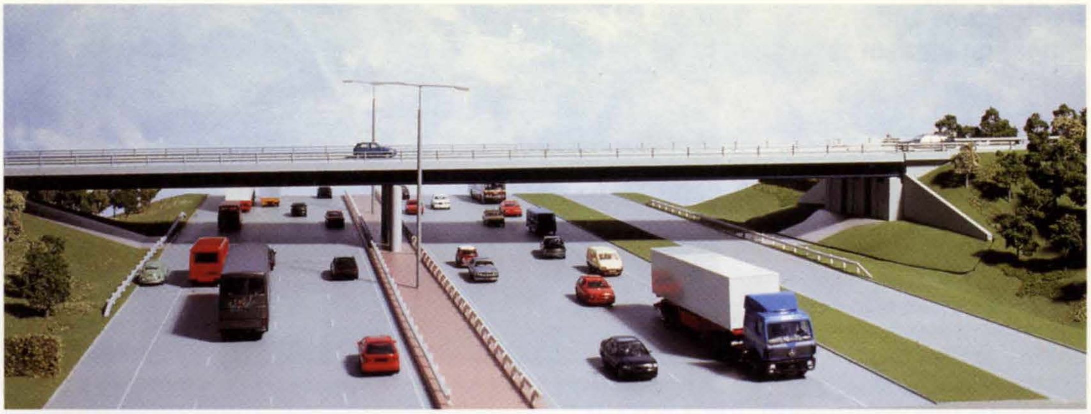


Structures
Richard Cooke

Widened motorways, particularly the 'parallel' schemes, require long-span bridges, with potentially unbalanced span arrangements, and the aesthetics of these need very careful consideration.

Experience gained on the recently completed M40 was the basis for the design approach, and presentation of the motorway widening bridge proposals to the Royal Fine Art Commission has been undertaken, with a highly satisfactory response from the RFAC. Overbridges will have spans in excess of 40m, so speed of erection and ease of construction point almost entirely in favour of steel composite construction.

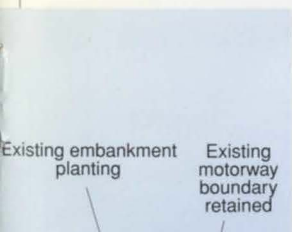
Computer modelling techniques were used initially to investigate the appearance of these structures, and subsequently physical models have been built. Equal attention is being paid to underbridges. Although they are not always visible to the motorway user they often have a greater impact on the local surroundings. Bridges crossing existing junctions, railways or rivers present difficult problems which have been carefully considered in the design.



10.+11.
Model of new overbridge designed by Arups for the M6.

Geotechnical issues
John Gabryliszyn

Some of the existing motorway network was built with only the most sparse geotechnical information. For example, on the original (1959) section of the M1, boreholes were regularly spaced at about 100m intervals along the centre line, with maybe one at each structure. On all these projects, widening is having to take place where earthwork failures have occurred both during and subsequent to construction. Rock cuttings, which had originally been designed on an empirical basis, are now subject to a more rigorous analysis. Restraints on the routing of more recent motorways have resulted in them passing through areas of poorer ground and contaminated sites. The limited nature of the early data presents its own challenges in relation to proposed widening schemes, as a need for much more detailed information now exists due to the requirement to extend the existing works. In addition, the proposed designs have to meet increasingly stringent codes of practice, and the amount of environmental protection legislation is a major determinant of geotechnical treatments. Arups' geotechnical engineers are therefore having to pay particular attention to the need to develop practical ways of dealing with the problems that arise, since there is no alternative other than to develop an engineering solution. The situation is unlike, for example, a by-pass proposal, where route alignment variations can overcome the more severe constraints. The widening proposals also deal with the addition of long, thin strips of new construction adjacent to existing embankments and structures, and it has been necessary to develop solutions to overcome the problems of differential settlement, and highly restricted working space. Particular problems also arise in site investigation, since the investigatory work has often to be undertaken under the severe constraints of working adjacent to a live motorway.



12. Existing rock cutting at Trentham in Staffordshire, on the M6 motorway.

Management and multi-disciplinary activities

Highway design is hugely interactive, depending on a range of engineering, transport planning, geotechnical, structural, environmental, and electronic skills. As with most other engineering designs, the solution which is eventually adopted is always a compromise. It is the sheer scale of the effort required in motorway widening schemes, and the range of skills throughout Arups that have had to be deployed, which make this work almost unique.

The firm's project management skills therefore have to be concentrated in the hands of the highways project managers, who have sufficiently detailed knowledge of a wide range of disciplines so that informed debate and probing of views can occur. It is however, not only the project manager who needs this ability; all team members across all the Arup disciplines have become aware of, and developed an interest in, the activities of other specialists. This multi-disciplined, integrated team approach is a key feature of Arups' approach to projects, and is vital in building and maintaining client and public confidence.

Traffic noise and mitigation measures

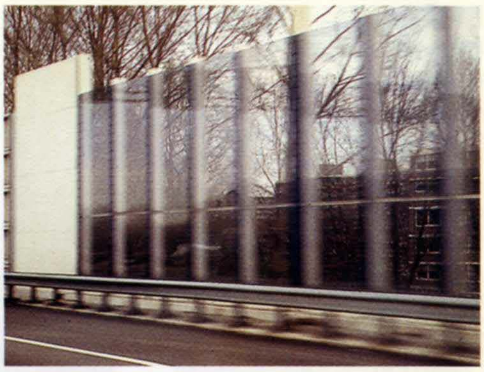
Colin English

Although there are standardized techniques for predicting traffic noise, they are not instantly adaptable to multi-lane carriageways, nor do the basic research sources deal with roads with the high levels of traffic flow now forecast.

Arup Acoustics have been closely involved with a wide range of road schemes, and they are at the forefront of extrapolating, developing, and adapting traffic noise prediction techniques to the special case of motorway widening.

While most of the techniques for environmental assessment and design are described in the DoT Design Manuals, it was felt necessary to develop a series of environmental design and mitigation objectives specifically for each motorway widening project.
In relation to noise, a key objective has been to actually reduce the high levels forecast at the roadside to acceptable levels at residential properties, and at all other noise-sensitive locations (e.g. schools, hospitals, etc.). Such a noise reduction runs counter to the widespread popular belief that widening would increase noise levels.
However, the sheer scale of the mitigation measures is becoming apparent. Acoustic barriers of 8-10m height are having to be considered, and these present significant visual and architectural challenges.
However, good design can do much to ameliorate their impact.

Arup Acoustics and Arup Environmental have looked at the best European practice, and have visited France and Holland to see how other countries are tackling this common problem.



13. High steel barrier in Paris, and right: 14. Transparent barrier in Holland: this reduces noise but also allows views out for the motorist.

15.+16.
Another Dutch solution:
this 'soft' hedge-like construction reduces the visual impact of a large barrier.

Driver communication systems

Iain Bell

The traditional system of matrix signals mounted in the central reserve conceals a largely hidden electronic network, but the information conveyed is quite limited, and often lags behind what is actually happening at that moment on the motorway. The next generation of widened motorways will need to be 'intelligent highways'. The range of information to be provided will need to embrace a new version of the national communications network (NMCS2), automatic incident detection (MIDAS), and variable message signing (VMS). The emphasis will be on real-time continuously updated information, and in-house expertise puts Arup Communications in an advantageous position in this field of transport informatics. Looming on the horizon is the possibility of tolling all motorways, which will add to the electronic networks within the road system.

17. Typical gantry over a dual four-lane motorway, with matrix signals for lane control and a variable message sign.

Public involvement

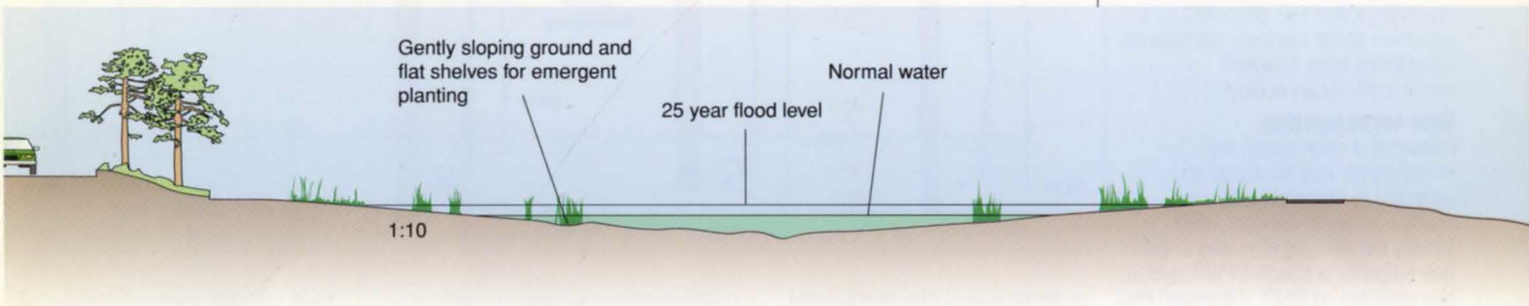
A particular feature of the planning process for road scheme is the involvement of the public. There are many stages throughout the life of a road scheme when contact with the public is needed. This starts from data collection, via interviews, continues through consultations with statutory and other interest groups, embraces exhibitions at various stages, and culminates at Public Inquiry. All of these require presentational and graphic skills of the highest order, but over and above this, professional judgements are being continually challenged and probed. Errors of judgement and faulty logic are rapidly exposed, and cross-examination at a Public Inquiry is the ultimate test of professional belief and skills. Since a road scheme can involve demolition of homes, acquisition of farming land, impact on industry, and adverse environmental effects, it is absolutely necessary to ensure that only the most thorough and professional work has been undertaken. Appearing at a major Public Inquiry, lasting probably several months, concentrates the pressure to produce only the highest quality work. Few other professions face that degree of challenge to their judgements, but it is a fascinating aspect to highway work.

Ecological issues

Andrew Bascombe

While widened motorways have a similar risk of affecting sensitive ecological sites or protected species to that of a new road, the fact that no new severance or pollution risk is caused is an advantage. Motorway widening can also provide the opportunity to create new habitats. Detailed ecological advice is essential to ensure that sympathetic engineering designs are chosen, also that mitigation and enhancement measures are designated into the scheme. Ecologists from Arup Environmental have provided a wide range of specialist skills which have been applied at all stages of motorway widening - services ranging from field survey and route appraisal, guidance on listed sites, species and habitats, design treatments, monitoring of construction, habitat management plans, and advice on balancing ponds, water quality issues and pollution control. Close liaison has been necessary in respect to ecologcal issues, for example in the design of balancing ponds, where drainage engineers, landscape architects, and ecologists need to maintain close liaison.

18. Balancing ponds have been designed to fit into the existing landscape.



19. Cross-section through typical balancing pond.

Credits

Clients:

Highways Agency Motorway Widening Unit (M1, M6, M42)

Highways Agency Eastern Regional Office (M25)

Consulting engineers:

Ove Arup & Partners: John Bevan, Tony Gibson, Phil Hall, Alan Hughes, Tony Jones, Mervyn Raisbeck, Terry Rawnsley, Colin Stewart, Andy Walker (highways), Richard Cooke, Tony Evans, Mike Larvin, Allen Paul, Colin Wilson (bridges), Aidan Eaglestone, Dave Thompson, Peter Webster (traffic forecasting), Phil Hall (economics), John Gabryliszyn, Tony Snedker (geotechnics), Paul Tomlinson, Simon Witney (environmental planning), Tom Armour, Benz Kotzen (landscape), Colin English, Clive Swift (noise studies), Andy Bascombe (ecology studies), Rob Paris (air quality), Iain Bell (communications), Peter Speleers (graphics)

(plus many other staff members, too numerous to list, in the Highways, Bridges, Environmental, Transportation, and Communications groups, and Arup Acoustics)

Landscape architects:

Landscape Design Associates (sub-consultants for the M1 widening only)

Illustrations:

1 Department of Transport
2 Denis Kirtley
5, 10, 11 Peter Mackinven
6 Tom Armour
3, 4, 7-9, 19
Trevor Slydel/Peter Speleers/Jon Carver
12, 17, 18 Ove Arup & Partners
13-16 Benz Kotzen

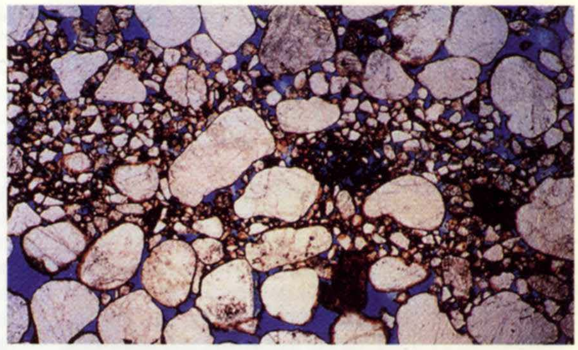
Summary

The attraction of the motorway widening programme, as of many other major civil engineering schemes, is the ability to work in a challenging environment, to interact with a wide range of specialist staff, and eventually to have one's professional judgement seriously criticised by informed laymen and interest groups.

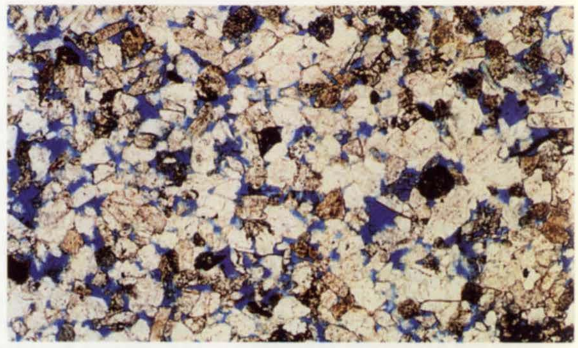
The roads programme, and the widening of existing motorways, is likely to be an increasingly politicized activity calling for managerial and technical skills of the highest order. This is the challenge that the firm is facing with utmost determination to design a product which will, in its own field, represent the Arup ideals.

Sellafield geotechnical study

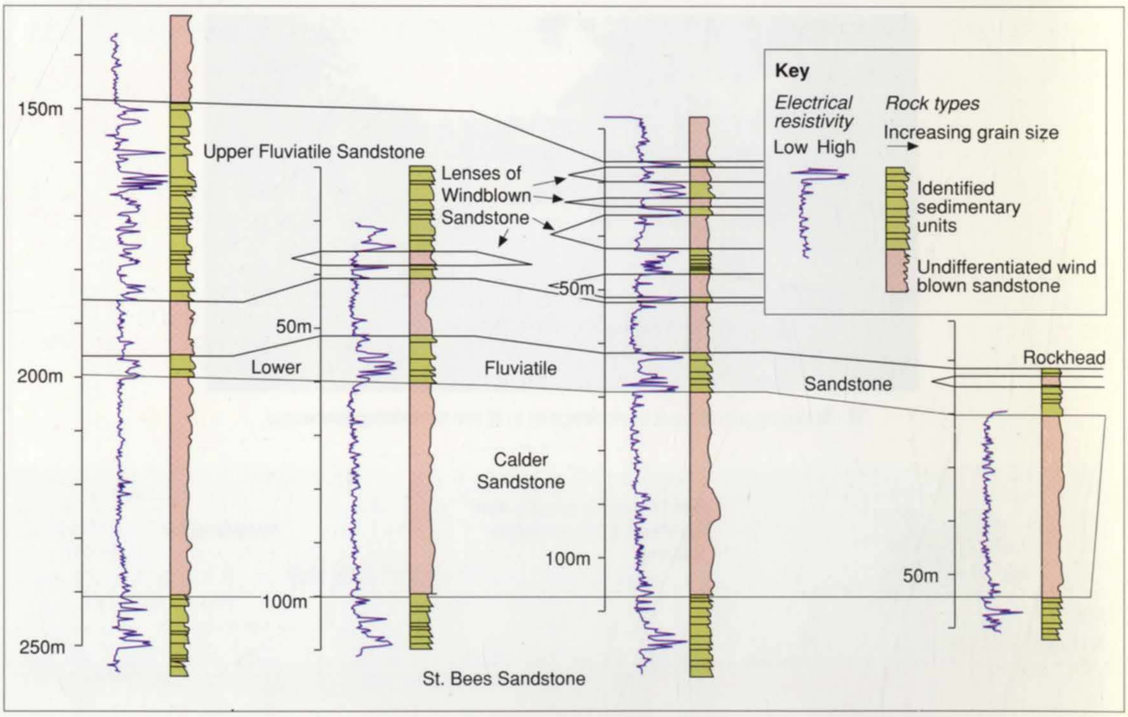
Colin Curtis
Andrew Law
David Pascall



2. above: Coarse-grained, well-rounded, windblown Calder Sandstone, and below: typical St. Bees Sandstone.



1. above, Wireline drilling to 300m depth. 3. below, Sample correlation of four boreholes across c.1km of site.



Objectives

British Nuclear Fuels plc (BNFL) are examining the feasibility of building new pressurized water reactors (PWR) at Chapelcross, Scotland, and Sellafield in Cumbria. Part of Arups' involvement has been to carry out, from October 1991, a geotechnical study at the latter site. The main objectives included:

- input into an Environmental Statement
- support to Site Licence and Planning Consent applications and subsequent Public Inquiry
- supply of data for the site safety case preparation
- input to the seismic hazard assessment study.

These were to be achieved through a major site investigation, concentrating on the geological structure and the hydrogeological and geotechnical aspects.

Site constraints

The investigation area, north of the existing Sellafield complex, is partly on the floodplain of the River Ehen, by the coast, and partly on higher ground to the east. BNFL obtained planning permission for the investigation, but this subsequently constrained operations. Since the floodplain was of environmental interest (it contained a natterjack toad colony), an ecological method statement for operating there was prepared as a condition of the planning permission. Operations were checked periodically by an ecologist.

Site investigation

Following a desk study, the investigation was tendered and awarded to Norwest Holst who started on site in January 1992. Initially the investigation was to be in one stage for a specific PWR station site selected by BNFL. However, this was modified by widening the scope of location for the station. The investigation was carried out in two stages: Stage A, which took six months, primarily concentrated on establishing the geological structure. The 10-week Stage B comprised special geological sampling by drilling, together with limited sampling and in situ testing for geotechnical purposes.

The Sellafield ground conditions comprise a variable thickness of glacial drift over a thick succession of relatively featureless red sandstones of Permo-Triassic age (c.200M years). One of the prime concerns at the start of the study was whether a stratigraphical correlation could be obtained in eitherthe drift or sandstones. Apart from conventional investigation techniques of boring and core drilling, the fieldwork was to include a seismic geophysical survey to examine the deep rock structure.

Stage A investigation

After initial boreholes a seismic refraction survey was performed to gain a rapid picture of the variation in drift thickness over the site and surrounding area. Small dynamite charges were set off, their refracted waves being recorded on strings of geophones. The refraction was followed by a reflection survey to look at the deep geological structure to depths of about 1km – the base of the Permo-Triassic rock. After interpretation of the results of these two surveys, a further reflection survey took place in the area of most suitable rockhead to gain a more detailed picture of the structure.

Simultaneously with the geophysical survey, drilling the first borehole proceeded. At 150m depth, signs of a change in the sandstone were observed that would permit stratigraphical correlation. It had been planned to lower wireline geophysical sondes down all the deep boreholes to measure electrical, acoustic and radioactive properties of the rocks.

Using these, plus information from investigation work at the neighbouring NIREX repository, the first borehole was continued to 300m depth to ensure it had penetrated the uppermost seismic reflector within the Permo-Trias. This reflector was the interface between the Calder Sandstone and the underlying St Bees Sandstone. This was penetrated by the deep boreholes and the sandstones were correlated (Fig.3) using lithological and geo-physical sonde logs. Deep drilling permitted the geological structure to be ascertained independently of the geophysical survey and delineated features not identified on the seismic interpretation. Trial pitting and static cone penetration tests were used to examine the drift materials. Two suites of downhole and crosshole geophysics gave velocity control for seismic processing and provided dynamic moduli values.

Stage B investigation

The main geological features identified by the seismic survey were investigated by drillholes during Stage B, and a potential fault zone was successfully cored over about 50m depth interval. Stratigraphical correlations indicated that any movement had ceased during the Triassic period. Up to three piezometers were installed in selected boreholes at different depths to facilitate monitoring of the groundwater pressures to examine seasonal and tidal influences. This information was incorporated in a hydrogeological model. Included in the laboratory testing was the production of photomicrographs from thin sections of rock core.

Interaction with other parties

During the study there were five meetings with the Seismic Hazard Assessment Team. Arups' desk study and final interpretative reports were reviewed by members of Atkins, Mouchel, British Geological Survey, Moffat Associates, and Gibbs. Two meetings with NIREX have been convened for them to assimilate the study findings into their regional structural geology maps.

Conclusions

The study was completed in August 1994. A study of this scope, covering nearly three years, is not a usual occurrence. With a total cost of £2.2M, it included some 21km of seismic survey and 1800m of core drilling. It provided a chance to use in situ testing techniques, such as wireline sonde logging, not commonly used in site investigations, as well as concentrate on establishing the deep geological structure.

The main conclusion was that the geological structure of the site would be suitable for a nuclear power station development.

Credits

Client:
British Nuclear Fuels plc

Geotechnical consultants:
Ove Arup & Partners Martyn Stroud, David Pascall, Andrew Law, Colin Curtis

Geophysics sub-consultant:
Quad Consulting Ltd.

Geotechnical contractor:
Norwest Holst Soils Engineering

Illustrations:
1. Andrew Law.
2. British Geological Survey.
3. Jon Shillibeer.

Sellafield seawater cooling system

Martyn Stroud
Hakop Mirzabaigian

Introduction

BNFL's possible new PWR site is situated north of their existing site at Sellafield. Because of its potential location close to the Irish Sea, the intention would be to supply cooling by seawater, which can either be provided direct or as a make-up water for cooling towers.

A comprehensive feasibility study was carried out to examine whether immersed or bored tunnelling techniques would be appropriate, with particular attention to construction costs, risks and uncertainties, and environmental issues.

The cooling system

This was proposed to comprise intake and outfall tunnels, connected to the pumphouse and the surge chamber at the power station site, and extending from the station facility into the Irish Sea. The water requirement for one PWR station is 66m^3/sec., and the hydraulics of a cooling system from pumphouse to intake and outfall structures were analyzed to give an optimum design, taking into account tunnel diameters, multi or single inlets and outfalls, and tunnel entry and exit design. Based on this work the tunnel diameter was established at 6m, with a flow velocity of 2.5m/sec. Computer modelling located the possible outfall and intake at 2.5km and 1.8km offshore respectively, making the overall lengths of the two tunnels 3km and 3.7km, measured from the proposed site to the intake and outfall shafts offshore. Their vertical alignments were dictated by the system hydraulics (Fig.1).

Geotechnical considerations

The general ground conditions encountered inland during site investigation were sedimentary deposits, both glacial and marine, as sands and gravels with boulders overlaying sandstone. Chiselling was necessary to keep construction of the boreholes going, and the evidence from the site investigation and visual inspection of the site area was that large boulders could be encountered during tunnelling. In addition, geophysical data from offshore indicated that the rock outcropped out to sea. Fig.1 also shows the typical geology of the site.

Tunnelling techniques

Three were evaluated, for their environmental impact, costs, and risks and uncertainties during construction. The techniques were immersed, bored through rock, and bored through overlying sedimentary materials.

Immersed tunnel

In this option the intake and outfall tunnels would be provided by:

- Cut and cover double tube (onshore): 1000m
- Thrustbore double tube under the railway and River Ehen: 100m
- Double immersed tube: 1900m
- Single immersed tube 700m

The onshore section of the tunnel would involve major dewatering and excavation support work, in an operation that would also involve dealing with large boulders. The offshore section was proposed to be dredged, though dredging through rock was considered to be difficult and expensive. The other risk involved with the immersed option was the weather conditions. The environmental impacts of using this technique, although mitigatable, were judged to be considerable compared to those of the bored tunnelling technique.

Rock-bored

Based on available information about the quality of rock, the tunnels would be some 80m below the Highest Astronomical Tide (HAT). Available information on the rock quality indicated that it was fractured with soft lenses. This could be dealt with by grouting and/or freezing the rock ahead of the tunnel face to increase stability and reduce water inflow. However, this would increase construction programme and consequent cost increases.

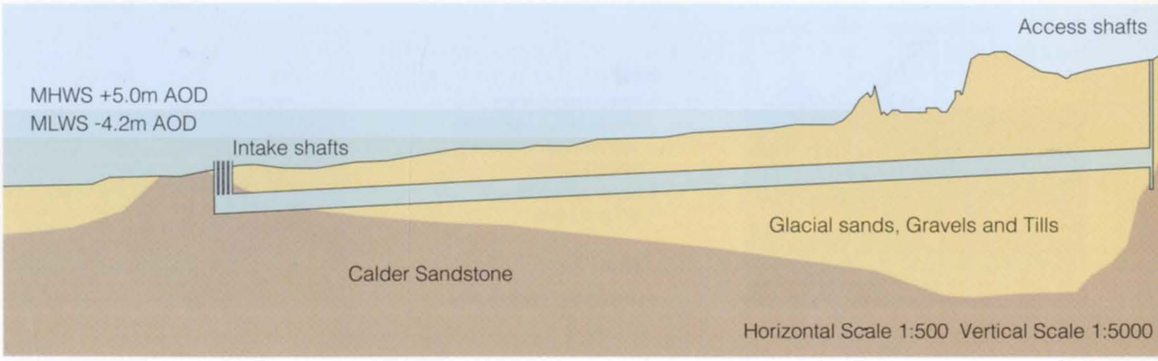
Soft ground bored

To ensure that they would be in reasonably competent ground, the study for such shallow tunnels aligned them with around two diameters' minimum cover, below both ground and seabed, throughout their length. Tunnelling machinery exists that is capable of dealing with the water pressure in the gravels, sands, silts and clays likely to be encountered. It can be adapted to deal with sandstone intrusion, and incorporates crushing equipment to deal with boulders up to 0.5m in diameter. It can cut through larger ones if they remain stationary, but if they are not sufficiently well fixed in the surrounding ground they could become dislodged and rotate with the cutting head. Some would be broken by the cutting head, but stronger boulders might have to be dealt with by men entering the face under compressed air at comparatively high pressures to break up manually the obstruction.

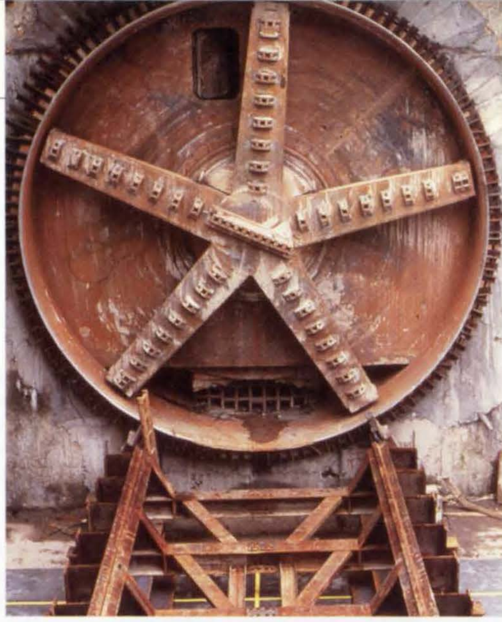
The selected technique

The immersed tube option was not chosen because of uncertainties from weather conditions, and environmental impact during construction. The rock tunnel option, though feasible, had inherent uncertainties due to zones of fractured rock, the need for grouting, and resulting costs. Because of the depth, the access shaft for tunnelling, not to mention the intake and outfall shafts themselves, would be very deep and consequently expensive to construct. Construction of the shafts would take longer, and be vulnerable to weather conditions.

The soft tunnelling option was therefore chosen, but to take account of uncertainties due to boulders the anticipated rate of progress was deliberately underestimated by 25%.

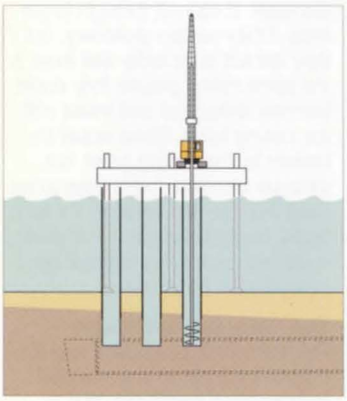


1. Tunnel alignment.



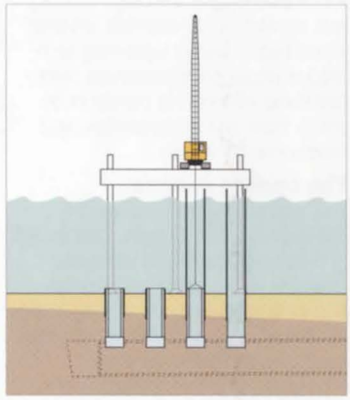
2. Tunnel boring machine.

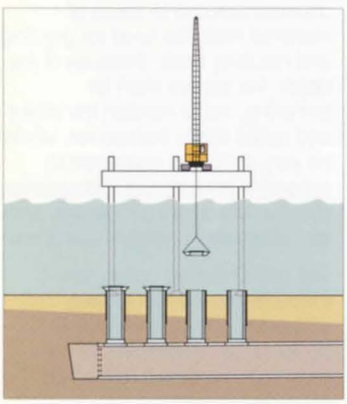
3. **(a - f)** Intake shaft construction.



◀ (a)
- Excavate shafts by auger and chisel using temporary casings keyed into rock.

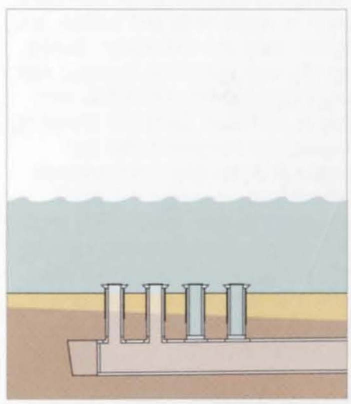
(b) ▶
- Place concrete plugs.
- Install precast concrete tube onto concrete plugs.
- Pressure grout annulus and cut off casings.
- Install precast concrete tubes onto concrete plugs.

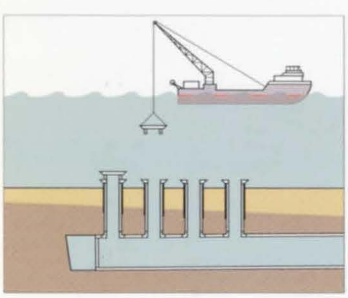




◀ (c)
- Place lower section of diffuser caps with temporary sealing plates.
- Bore tunnel and install 'knock-out' panels.

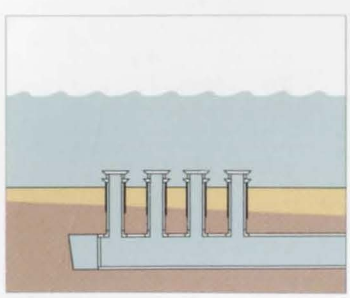
(d) ▶
- Remove jack-up barge.
- Abandon non-salvageable elements of TBM.
- Construct end of tunnel.
- Break through into shafts and drain off water.





◀ (e)
- Flood tunnel when connection is complete and remove temporary sealing plates.
- Install top section of diffuser caps.

(f) ▶
- Completed intake tunnel.



Bentonite tunnel boring machines (TBMs) were proposed (Fig.2), suitably equipped to drive through both superficial deposits and rock. They would be designed to use a thixotropic bentonite fluid both to support the excavation face and remove the spoil cutting. Face support is maintained by pressurizing the bentonite to give the correct support pressure for ground and water load, but the TBM's design restricts pressurization to the cutter head and so allows work in the tunnel in free air. The fluid containing the spoil cuttings is pumped from the face to the surface; the spoil is extracted and the fluid returned to a reservoir for re-use in the tunnel.

Intake and outfall shafts

Intake would be by four 3m diameter shafts, the riser and diffuser for each being built inland. The shafts would be constructed and capped off to render them watertight before the tunnel reached their location. The construction sequence is shown in Fig.3. The advantage of this is that the shafts could be constructed early on, during suitable weather windows, and independent of tunnelling operations. Tunnel/shaft connections could be made once both operations were complete.

Programme and cost

The construction period for the whole system from the date of placing the order for the TBM is estimated at 45 months, whilst the cost estimate for its elements is as follows:

• Access shaft	£3 100 000
• Tunnels	£46 790 000
• Intake shaft	£2 200 000
• Outfall shaft	£3 100 000
• Design and engineering costs	£925 000

Conclusions

This study was very important to the overall feasibility of building the PWR at Sellafield, and the techniques proposed by Arups were discussed in detail with international contractors who have extensive experience in this field, to ensure the buildability of the cooling system. Further work would only be undertaken if BNFL formally decided to proceed with any development.

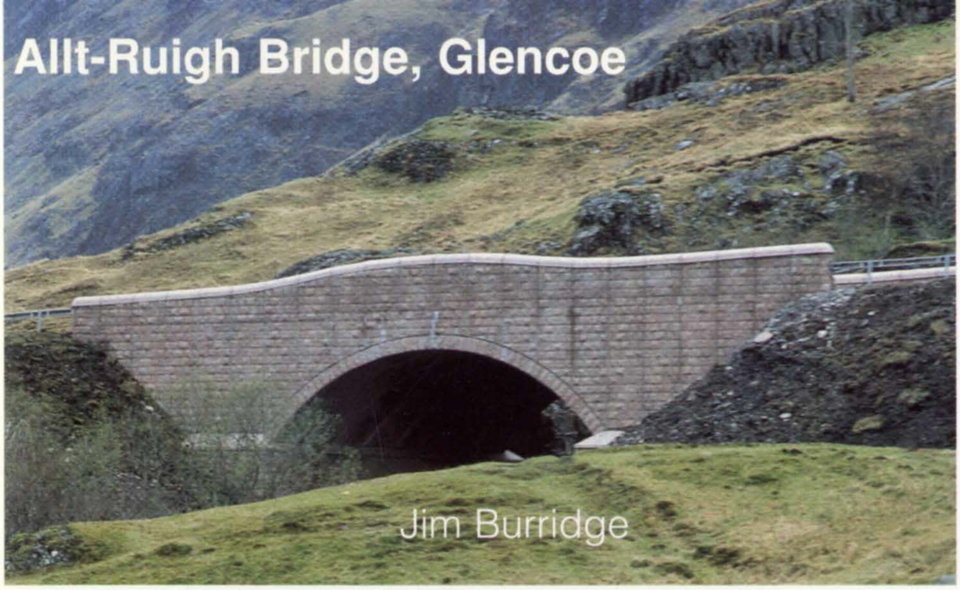
Credits

Client:
British Nuclear Fuels plc

Tunnelling consultants:
Ove Arup & Partners Ian Askew, Oliver Bevan, Ulric Gerry, Paul Holder, Robert Hyde, Roger Milburn, Hakop Mirzabaigian, Douglas Parkes, John Senior, Martyn Stroud, Mike Wilton

Illustrations:
1. & 3: Nigel Whale
2: Hakop Mirzabaigian

Allt-Ruigh Bridge, Glencoe



1. The bridge in its Highland setting, with the slopes of Am Bodach rising behind.

Introduction

In 1992 the Scottish Office Industry Department Roads Directorate launched a national two-stage competition for a new bridge to take the A82 over the Allt-Ruigh (red burn), replacing an existing 1930s reinforced concrete, granite-clad structure. The site lies nearly 150km north west of Glasgow. The first stage established design principles, and five submissions were chosen to be developed. The winner, by Ove Arup & Partners' Newcastle office, was selected in May 1993 by the client and his advisers, after which a presentation to the Royal Fine Art Commission for Scotland was made. The design/build fixed cost contract was awarded to Laing Scotland in June 1993 with a programmed start on site the same August.

The design

The remote Highland location, weather, access constraints, and environmental issues all pointed to maximum off-site preparation. In addition, eight criteria had been laid down in the competition, addressed by Arups' design as follows:

• *Arched form*

The concept used precast reinforced concrete arch units to create a structure able to take the maximum highway loading requirements. Rigorous analysis confirmed the robustness of the design for a long and useful life.

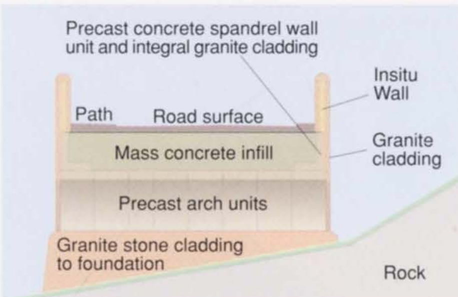
• *Innovation in design and construction*

The design aimed for maximum repetition, with two forms only being used - one for the arches and the other for the wing and spandrel wall elements. Finishes to the wing walls were integrally cast and arrived factory-finished ready for erection. In situ reinforced concrete foundations support the precast arch units, accomodating various ground levels, and the strip footings for the wing walls similarly follow the ground profile. With the precast wing walls and arch elements erected, the spandrel walls were placed on the arch and the permanent 'formwork' thus created infilled with mass concrete to provide severally a composite arch, restraint to the spandrel walls, and a base to the road. This composite approach made for efficiency, buildability and robustness, the simplicity of the design allowing very short construction time in potentially difficult weather conditions.

• *A design with adaptability for use on other sites*

The same precast 'formwork' can be used because different spans are possible from greater or lesser sections of the same radius arch. Arches of variable skew could also be achieved by a similar approach, whilst wall units of variable height could be cast from the same form. Finishes could either be integrally cast with the wall units or an exposed concrete surface provided, depending on budget and location. All this gives a flexible 'kit of parts' for 7-20m spans, with variable angles of skew up to 30°, and allows alternative finishes and parapet forms. Variations in ground condition make the in situ foundations the only element that inevitably alters from site to site.

2. Cross-section: 6.3m roadway between 0.6m and 1.6 pavements.



• *Integration into the landscape*

Study of the area led towards orientating the arch to emphasize the gorge-like nature of the stream at this location. The wing walls were kept parallel to the road to minimize visual intrusion on the gorge, as well as maintain a focus upon the arch.

• *Minimal disturbance of the site during construction*

This was achieved by locating the new wider bridge in almost the same position as the existing. One new section was to be built alongside, with single-lane traffic transferred to it whilst the existing bridge was demolished and the second phase of the new bridge constructed. Existing flora and fauna were surveyed before commencing work, to identify how existing topsoil and plants could be removed, stored and re-used in landscaping and restoration at the end of the project.

• *Appropriate appearance*

The weathering of the existing bridge disguised very well the originally pink granite cladding to its concrete structure. To meet client concern over durability and concrete protection, as well as aesthetic considerations, masonry cladding was required for the new bridge. A modern equivalent to the original was found west of Aberdeen and used to provide the pink granite cladding finally chosen. Stone patterning, textures, and parapet profiling were all considered in some detail before the final choice, as were other principal elements.

• *Suitable finishes*

Corrienie pink granite is well known for its durability. A split-faced appearance was chosen for the main walls, whilst the feature elements have a smoother finish. The soffit of the arch is the only unclad exposed concrete element.

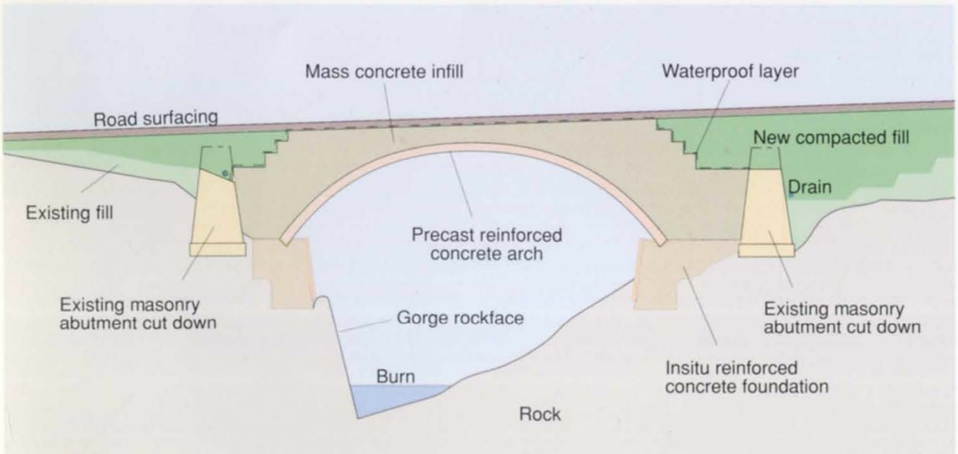
• *Very high levels of durability*

These were sought by using stainless steel for the reinforcement; grade C50 concrete with aggregates of proven durability; granite facing; and by factory precasting the main concrete elements to achieve greater quality control.

Construction

Work commenced in August 1993, with two-lane traffic having to be maintained until the beginning of September. In the event the two-stage construction approach was revised due to supply difficulties: a bailey bridge carried single-lane traffic while the existing bridge was demolished, and both phases of the new were built in one operation. The precast approach proved itself with fabrication, delivery and erection taking some six weeks, and the new Allt-Ruigh was opened to two-lane traffic on 24 December 1993.

3. Long section: The clear span of the arch is 11m.



Credits

Client:
Scottish Office Industry Department: Roads Directorate

Designer & engineer:
Ove Arup & Partners Robin Anderson, Jim Burridge, David Jameson, Steve Pearce

Contractor & design/build client:
Laing Scotland

Environmental consultant:
Institute of Terrestrial Ecology

Client's advisers:
Scottish Natural Heritage
Gillespies
National Trust for Scotland
Crouch Hogg Waterman

Illustrations:
1: Jim Burridge
2, 3: Sean McDermott/Trevor Slydel

Printed in England by Reedprint Limited, Windsor, Berkshire