Civil and structural engineering design for the Elizabeth line station at Tottenham Court Road

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Synopsis

The new Elizabeth line station at Tottenham Court Road, delivered by the Crossrail programme, has been an exercise in interface management as well as a feat of engineering.

This paper describes the design carried out by the Arup Atkins Joint Venture (AAJV) under contract C134, principally of the Western Ticket Hall box. Nestled in Soho, this was developed within a dense urban grid and the constraints of a residential oversite development above.

The team worked closely with London Underground Ltd's engineers at the Eastern Entrance, which was delivered as part of London Underground's own station upgrade works.

The tunnel for the eastbound Elizabeth line passes through the Western Ticket Hall box, which also provided construction access for the sprayed concrete-lined platform and concourse tunnels. Access dates to the site meant that there was insufficient time to complete construction of the box before the arrival of the tunnel boring machine (TBM). Consequently, the need to complete the excavation became critical and the team adopted a bottom-up construction sequence for one of the deepest open shafts ever excavated in central London. The box, formed of elements of diaphragm walls and raft, was constructed before the TBM arrived, and the remaining internal elements completed afterwards.

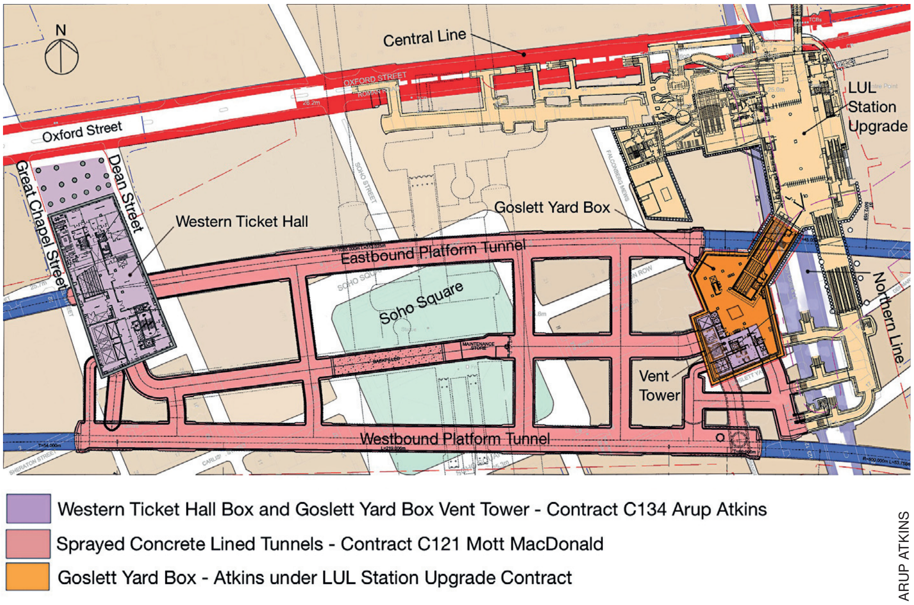

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Figure 1
Tottenham Court Road station plan showing division of design contracts

NOTATION

AAJV	**Arup Atkins Joint Venture**
MEP	**mechanical, electrical and public health**
OSD	**oversite development**
TBM	**tunnel boring machine**

Introduction

Tottenham Court Road Elizabeth line station consists of two entrances housed in box structures at either end of the platforms, both formed within diaphragm walls. These house access and circulation spaces, as well as tunnel ventilation systems and mechanical and electrical services. Between the two boxes, sprayed concrete-lined tunnels house the platforms and concourses, with sub-platform service connections to the boxes.

The structural engineering design of the station was carried out under three separate contracts (Figure 1):

- The below-ground shell of the eastern end of the station, known as the Goslett Yard Box, which connects into the new ticket hall of the London Underground station, was designed and built under London Underground's Tottenham Court Road Upgrade contract, with the design carried out by Atkins.
- The sprayed concrete-lined platform and concourse tunnels were designed under Crossrail Contract C121 by Mott MacDonald.
- The Western Ticket Hall box, ground level and five-storey ventilation tower structures, at the west end of the station, were designed under Crossrail Contract C134 by Arup Atkins Joint Venture (AAJV). This contract also included the internal structures in the platforms and concourse

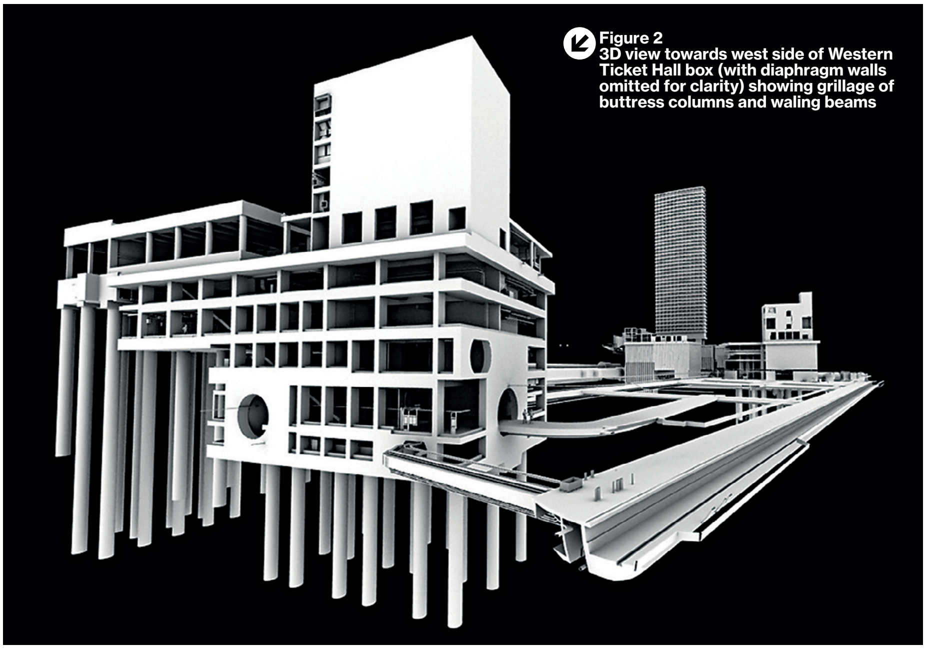

Figure 2
3D view towards west side of Western Ticket Hall box (with diaphragm walls omitted for clarity) showing grillage of buttress columns and waling beams

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tunnels, the internal fit-out structures in the Goslett Yard Box and a five-storey reinforced concrete tower above the Goslett Yard Box housing ventilation and other plant.

Although the structural design responsibilities were split, the overall responsibility for planning, architecture, building services, specialists and constructability for the whole station resided with AAJV, with Hawkins\Brown as architects, under the C134 contract.

Structural arrangement of the Western Ticket Hall box

The Western Ticket Hall site is located on the south side of Oxford Street between Dean Street and Great Chapel Street (Fig. 1). It is approx. 80m × 30m in plan and is split into two blocks by Fareham Street. The north block contains the ticket hall and station entrance at ground level, as well as retail units fronting onto Oxford Street. The ground level of the south block contains an electrical substation and an emergency escape and intervention access. A six-storey tower housing the tunnel ventilation systems occupies part of the site, and the remainder of the south block is given over to retail units.

Above both blocks, provision has been made for future six-storey residential oversite developments (OSDs). The ventilation tower acts as the stability core for the south block of the OSD. A stability core and shear wall provided in the north block are designed to resist lateral loads from both the ticket hall and future OSD. The ticket hall itself features a single central column supporting a grillage of post-tensioned roof beams. These beams support column loads from the OSD and form a primary visual feature of the entrance.

> **"THE RESULTING GRILLAGE IS STIFF ENOUGH TO FRAME THE ESCALATOR VOIDS WITHOUT THE NEED FOR FLYING PROPS"**

Below ground, the site consists of three sections. Adjacent to Oxford Street there is a single-level basement formed within cast *in situ* retaining walls which will house retail units. To the south of this are two sections of diaphragm walled box, 12m and 28m in depth, which house the station. The shallower 12m deep box contains two levels of basement and is located below the ticket hall. The deep box occupies the south end of the site and contains five levels of basement.

The platforms are reached directly from ground level by a dramatic single bank of three escalators. The eastbound line passes through the deep box, allowing direct access to the eastbound platform from a lower concourse at Level –4. Access to the westbound platform is via a 7m diameter concourse tunnel. Draft relief and service tunnels connect from the westbound tunnel into the deep box. There are four cores containing stairs, lifts, building services and ventilation risers.

The box was formed using diaphragm wall panels with a 1.8m deep piled raft in both the shallow and deep sections. There are five levels of 700mm thick propping slabs (including the ground floor). Vertical support is provided by a mixture of columns (including composite concrete-encased steel sections) and core walls. The propping slabs are flat, except at Level –3 where a grillage of drop beams is provided to form the roof of the lower concourse area, mirroring the beams in the roof of the ticket hall.

There are a number of transfer structures (described further below) formed of reinforced concrete deep beams and storey-high concrete-encased steel trusses. Buttress columns around the perimeter of the box provide a direct load path for the perimeter columns of the station above. They are also tied to waling beams that frame the large voids around the escalators and the tunnel ventilation ducts. The western diaphragm wall was positioned as far west towards Great Chapel Street as possible in order to accommodate the waling beams and buttresses sized for this purpose. The resulting grillage is stiff enough to frame the escalator voids without the need for flying props (Figure 2).

The diaphragm walls of the deep box are penetrated at three levels by tunnel openings. At Level –3, an opening was formed on the south wall to connect the draft relief shaft from the westbound running tunnel. At Level –4, there are openings for the concourse tunnel on the south wall, and the eastbound running and platform tunnels on the west and east walls respectively. At Level –5, there is an opening for a service tunnel connection to the westbound running tunnel. At each level, 1200mm thick reinforced concrete lining walls were provided around the openings. The purpose of the lining walls is to transfer vertical loads around the openings. The concourse tunnel opening to the south wall of the box is located immediately below a deep beam supporting the ventilation tower. A heavily reinforced beam strip was provided within the lining wall above the opening to deal with this. Similarly, the opening for the eastbound platform tunnel is located below one of the buttress columns.

The lining walls also act to tie the diaphragm wall panels together where they are cut by the tunnel openings, and contain the termination of the waterproof layer of

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the sprayed concrete tunnel lining where it extends through the openings into the box. This is described in more detail further on.

Storey-high transfer trusses are provided in three locations. A pair of trusses transfer column loads from the south block across the eastbound platform (Figures 3 and 4). These are located at Level –3. They are formed from 356mm × 406mm × 634mm universal columns. The diagonal members are encased in 850mm × 850mm reinforced concrete sections, while the bottom chords sit within the 1250mm × 1700mm deep drop beams. A third transfer truss (Figure 5) is provided at Level –1 below the highly loaded central column of the ticket hall (Figure 6) in order to spread the load into the piled raft foundation.

The walls of the ventilation tower act as deep beams below ground level to transfer the weight of the tower onto a line of columns at lower concourse level.

A bank of three escalators connects the ticket hall at ground level directly with the platform concourse at Level –4, a level difference of approx. 23.5m, with space provided for a fourth escalator to be installed in the future if required. The escalators are located above a 450mm thick inclined slab (Figure 7) which spans between the propping slabs, with the intersections between the inclined slab and the propping slab reinforced as beam strips. The supports for the escalator trusses are located close to these beam strips and plinths are provided on the inclined slab at the support positions. The escalators are designed to be maintained from above, with only a limited clearance between the bottom of the truss and the inclined slab.

The single-level basement for the retail units on the north side of the shallow box has a 350mm thick base slab supported by piles and an arrangement of pile caps and ground beams.

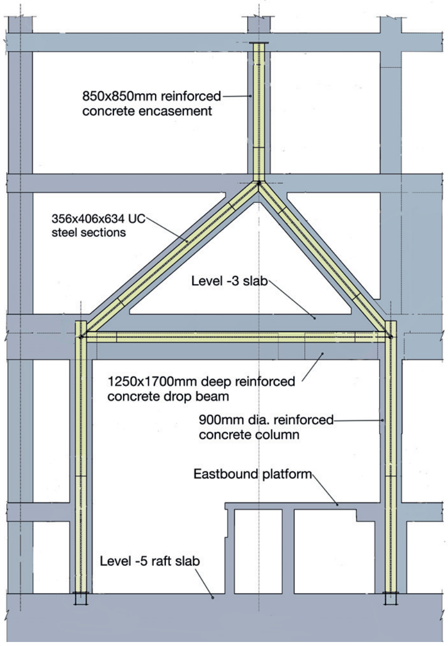

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Figure 3
Concrete-encased steel transfer truss above eastbound platform


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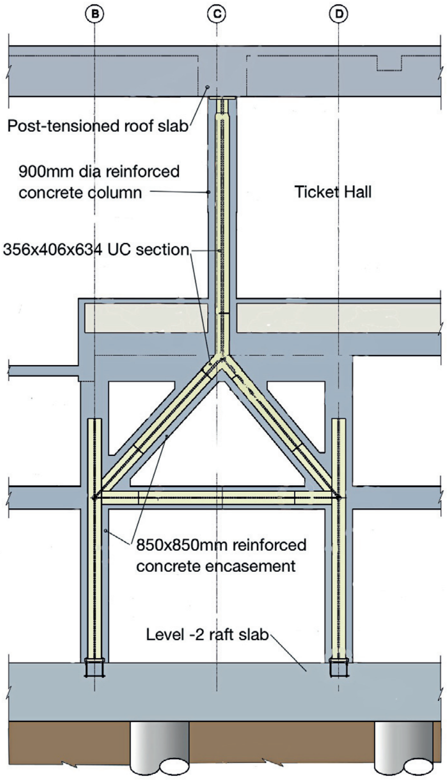
Figure 4
Installation of steel transfer trusses above eastbound platform

Figure 5
Concrete-encased steel transfer structure supporting main column to ticket hall roof



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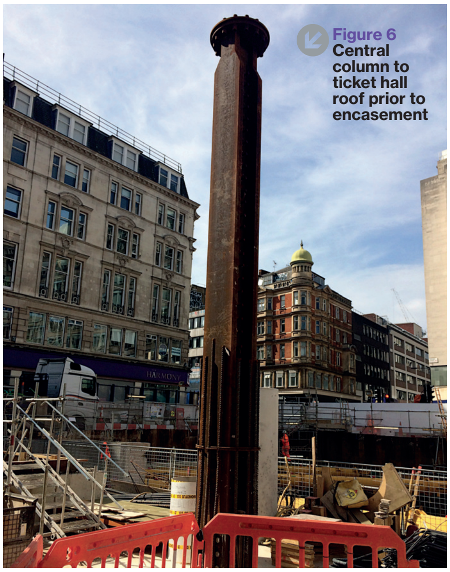
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Figure 6
Central column to ticket hall roof prior to encasement

Water tightness throughout the station boxes and the basement to the retail units is ensured by drained cavities in front of the perimeter walls and by an 'egg crate' over-slab drainage system.

Structural arrangement of ticket hall roof

The ticket hall roof (Figure 8) is formed from eight rows of 1000mm × 1550mm deep rib beams, running east–west at 3.75m centres, spanning between edge beams and a 1500mm × 1550mm deep central spine beam and a core wall. The edge beams are supported by perimeter columns at 7.5m centres. Two rows of 750mm × 750mm deep spreader beams run north–south at the mid-span of the rib beams. The roof is required to act as a transfer structure supporting column loads from a future six-storey concrete-framed residential OSD. It was decided at an early stage of the design that the beams forming the roof should be post-tensioned. This was to minimise the size of the beams, which are a key architectural feature of the station entrance, and to control flexural cracking as they are loaded by the OSD.

The design life of the station structure is 120 years, whereas that of the OSD is 50 years. The design of the roof had to allow for the OSD to be demolished in the future. As a result, it was not possible to use a staged stressing of the tendons during construction of the OSD. The design is therefore less efficient than it could otherwise have been. The high compressive

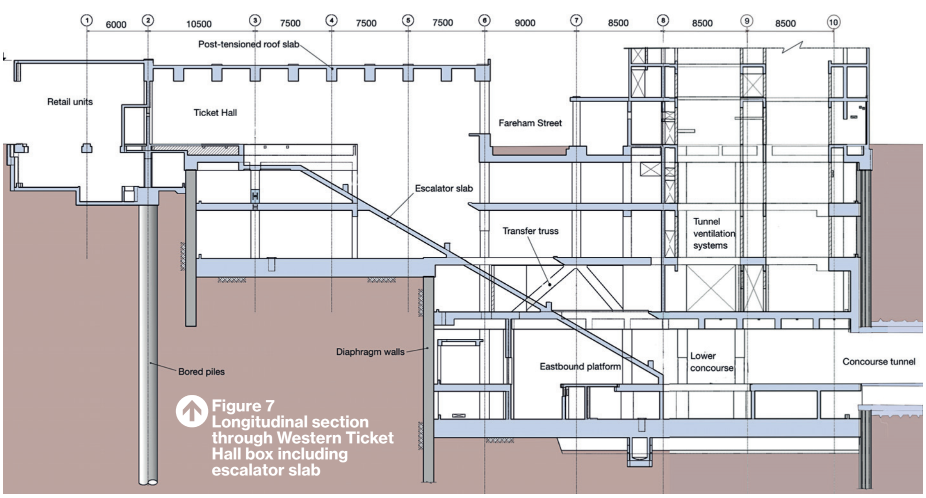

Figure 7
Longitudinal section through Western Ticket Hall box including escalator slab

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Figure 9
View of end block to post-tensioned spine beam

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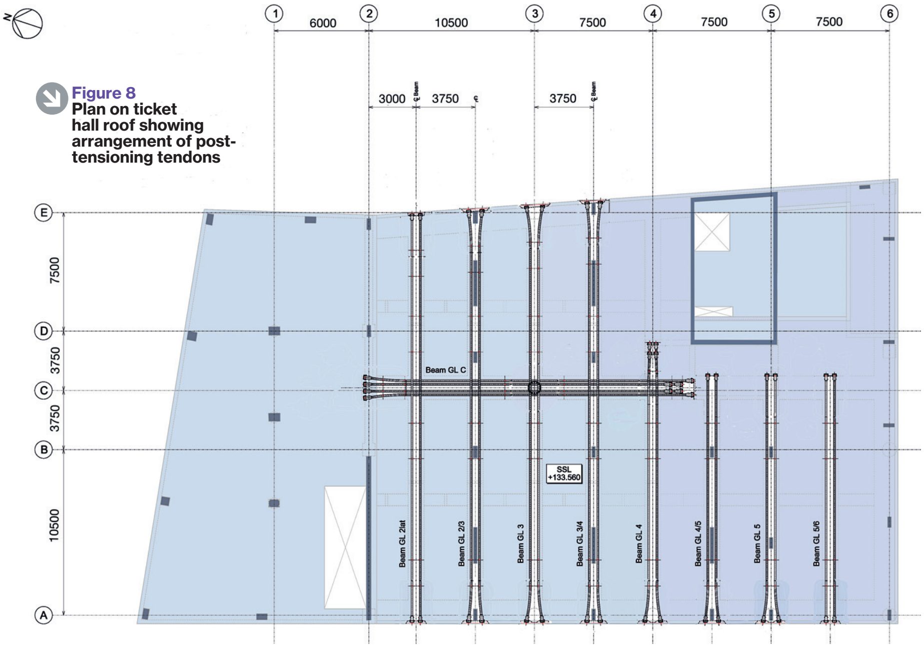

Figure 8
Plan on ticket hall roof showing arrangement of post-tensioning tendons

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stresses resulting from the post-tensioning required a considerable density of bursting steel around the end blocks (Figure 9) and the use of a relatively high-strength C50/60 concrete mix with a 10mm aggregate.

The OSD columns will be located on four of the eight rib beams. Consequently, the arrangement of the ducts varies between beams. The rib beams have arrangements of either four or six ducts with 19 strands or 22 strands per tendon. The central spine beam has eight ducts with 22 strands per tendon (Figures 10 and 11).

The roof slab was cast over a period of approx. eight weeks in the summer of 2016. The stressing of the first tendons (Figure 12) started within a week of the last section of slab being cast, by which time the concrete in the last pour had achieved the required minimum cylinder strength of 35N/mm^{2}.

The OSD loading for which the roof slab was designed was based on a scheme design developed in 2010. However, during the construction phase the OSD's interior planning was updated to increase its commercial potential, in particular the entrance areas. In the meantime, planned acoustic testing of the completed raft slabs showed that sound and vibration levels transmitted to the OSD from the adjacent Central line (London Underground) might be unacceptable. It was therefore necessary to make provision for acoustic isolation

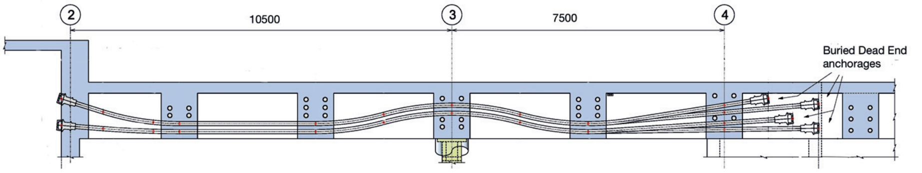

Figure 10
Section through post-tensioned spine beam showing arrangement of tendons

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Figure 11
View of post-tensioned roof beams during installation of tendons

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bearings between the station roof and the OSD. Both these events resulted in design changes to the arrangement of the roof, including the addition of 100mm high plinths to support the isolation bearings. Although the total loading from the updated OSD scheme was broadly in line with the safeguarded loading, changes to the distribution of loads required a detailed check of the roof structure against the original design.

Coordination with architectural design

Architectural design for the C134 contract was led by Hawkins\Brown Architects, who had previously completed the design of the adjacent upgrade works to the London Underground station at Tottenham Court Road. The architectural, structural and building services teams worked closely together to develop a coordinated design for the station. The design includes large areas of visual concrete, including the soffits of the public areas and the columns. Many of these elements were densely reinforced and, in some cases, included cast-in steel sections making the achievement of a high-quality finish extremely challenging. The success of this element of the design was therefore very much dependent on the skill and experience of the contractor.

Separated by platforms over 250m in length, the two entrances emerge in very different areas of central London. While the Eastern Ticket Hall's design sits within the bright commercial modernism of Centre Point at the intersection of Tottenham Court Road and Oxford Street, the design of the Western Ticket Hall reflects the darker, denser urban grid of Soho and the hi-tech industries that have occupied the older buildings in that area.


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Figure 12
Stressing of tendons to roof beams

"THE STRESSING OF THE FIRST TENDONS STARTED WITHIN A WEEK OF THE LAST SECTION OF SLAB BEING CAST"

The concept for the Western Ticket Hall roof reflects this, with a single central column and grillage of unclad ribbed and spine beams. This creates a slightly industrial structural aesthetic which is finished off neatly by bright bespoke stainless steel lighting drums (Figures 13 and 14) which are a signature feature of the station design. The drums were sized to sit neatly within the coffers between ribs to create a flush soffit.

Fortunately, C134 was commissioned for the design work to support a Schedule 7 Planning Application for the OSDs at the Western Entrance concurrently with the design of the ticket hall itself. This enabled the structural grid of the ticket hall roof to be optimised and coordinated to suit the residential planning grid of the OSD above, resulting in an efficient transfer system.

As part of value management undertaken in response to the Coalition Government's Spending Review in 2010, a link tunnel connecting the Western Ticket Hall and the Central Line was omitted. This had a series of knock-on effects on the design which allowed the internal arrangement of the box to be completely re-planned and simplified. The most significant change was the introduction of a single bank of escalators connecting the ticket hall at ground level with a new lower concourse at platform level (Level –4). This allows natural light to penetrate deep into the station, assisting with wayfinding.

The Level –3 propping slab above the lower concourse was formed into a grillage of downstand rib and spine beams, similar to that in the ticket hall. The downstands contained the lower chords of the transfer trusses and the ties of the strut-and-tie system used to transfer the walls of the ventilation tower above. The coffers are

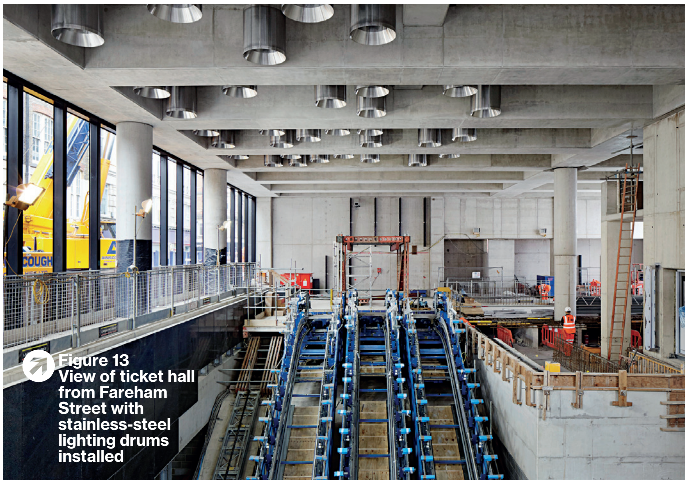
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Figure 13
View of ticket hall from Fareham Street with stainless-steel lighting drums installed


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Figure 14
Close-up view of stainless steel lighting drums between post-tensioned roof beams

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Figure 15 Station entrance and ticket hall

again used to house the lighting drums, unifying the appearance of the public areas of the Western Ticket Hall box (Figures 15 and 16).

Externally the station is split into two distinct blocks separated by Fareham Street, which was completely enclosed within the worksite during construction. It is being reinstated approx. 7m further north from its original position. This creates more space in the south block to accommodate the ventilation tower and electrical substation. The appearance of the station facades is coordinated with the design of the future OSD. The northern block containing the ticket hall is clad in panels of polished black concrete. The southern block is clad with panels of glazed bricks (Figure 17).

The ventilation tower above the Goslett Yard Box will eventually be covered by the OSD, but until that time it will be highly visible from Charing Cross Road. It was therefore specified to have a visual concrete finish with the joints between formwork panels and the tie holes arranged in a regular pattern (Figure 18).

Coordination with MEP services

Public circulation areas are located at ground level, Level –2 and Level –4. The remainder of the station box is largely occupied by mechanical, electrical and public health (MEP) services, with Level –5 given over entirely to distribution of services and ventilation ducts between the platform tunnels and service risers. Coordination between MEP services and the structural

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Figure 16 Image of lower concourse and eastbound platform at Level –4 design benefited significantly from three-dimensional (3D) modelling (Figure 19).

A large volume of the station is taken up by the tunnel ventilation systems. These are housed in ventilation towers at each end of the station which rise from Level –3 at approx. 15m below ground to Level +6 at approx. 20m above ground. The ventilation tower in the Western Ticket Hall box is located directly above the concourse area at Level –4 and is supported by concrete-encased steel-composite columns, with the lower sections of the ventilation tower walls acting as deep beams. Both towers house three fans with an internal diameter of 2.5m located at ground level to allow maintenance access directly from street level (Figure 20).

The draft relief connections to the western ventilation tower are made via a tunnelled connection from the crown of the westbound platform tunnel directly into the ventilation tower at Level –3 and through an opening in the Level –3 slab above the eastbound trainway, which connects to the ventilation tower via a duct. Heat from the trains is extracted through openings in the trackside edge walls below the platforms and ducted underneath the platforms to the Western Ticket Hall and Goslett Yard boxes at Level –5 before joining risers to connect to the ventilation towers at Level –3.

A network of water pipes was cast into the outer cover zone of the diaphragm walls and the internal piles. These were routed through the capping beams to allow the future installation of a ground-source heat pump system serving the OSD.

Design of diaphragm walls and foundations

Both the western and eastern boxes at Tottenham Court Road are formed with diaphragm walls to similar depths. Inside the boxes there are deep-level large-diameter bored piles to support the internal structure and retain the raft slab against future heave and water pressures. The western box has a split-level foundation with a dividing diaphragm wall (Figure 21).

All diaphragm walls are 1m thick with panel lengths of approx. 3m and are reinforced with conventional reinforcement. The shallower panels have a toe level 18m below existing ground level while the deeper box panels are 41m below ground level. All bored piles are 1.8m diameter. The deepest piles have toe levels 48m below ground level and a cut-off level 27m below ground level within the lower raft slab. The toe level of the shallow bored piles is 38.5m below ground level with a cut-off level 12m below ground level within the upper raft slab. Both rafts found on the London clay layer. This is a relatively thin stratum in this area and the lower raft is close to the interface with the Lambeth Group below.

The diaphragm walls have penetrations on most elevations for access routes, ventilation and train ways. Internal lining walls were provided to transfer vertical loads around the openings and support the remaining stubs of diaphragm walls against earth pressures. All openings for tunnels allowed for the provision of waterproofing at the interface, which was ultimately designed by others.

The Western Ticket Hall box was constructed bottom-up. This was dictated by the need to reach founding level early to facilitate the passage of the tunnel boring machine (TBM) drive forming the eastbound alignment through the box. The walls were designed using Oasys Frew[1], a 2D analysis package. More rigorous analysis of soil–structure interaction was undertaken using PLAXIS[2] when a greater understanding of soil movements was required.

Piles were also conditioned by the two extreme load cases of full support of the station structure including the future OSD and the minimum load case of excavated


Figure 17 View north up Dean Street and into Fareham Street showing different treatments of facades to north and south blocks

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> **"A LARGE VOLUME OF THE STATION IS TAKEN UP BY THE TUNNEL VENTILATION SYSTEMS"**

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Figure 18
Panelised finish to Goslett Yard Box ventilation tower with expressed formwork joints and tie holes

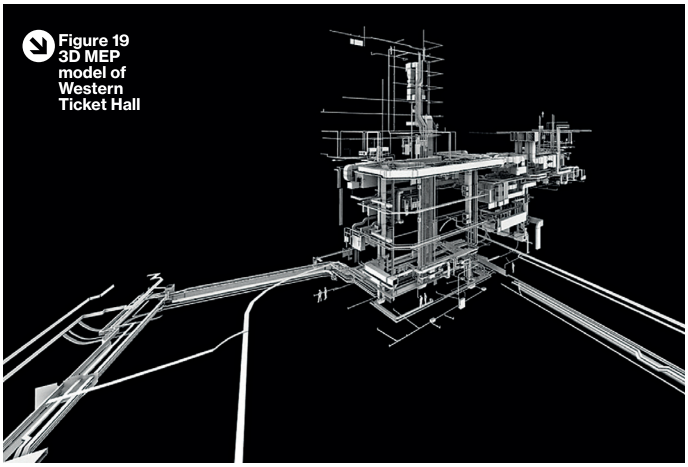

Figure 19
3D MEP model of Western Ticket Hall

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Figure 20
Installation of ventilation fans at ground level in Goslett Yard Box ventilation tower

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'empty' box with full application of water pressure and heave resulting in tension within the piles.

The raft structure was similarly bounded by these ground conditions, acting both as a conventional ground-bearing raft with piles and a diaphragm transferring water pressures and heave loads to the piles. The raft was analysed using Oasys GSA Raft[3], an iterative software package which allows soil–structure interaction to be modelled using an embedded Oasys Pdisp program[4].

The foundation design evolved through a number of variations to the construction sequence, including having the TBM pass through either before or after excavation of the box. Both top-down and bottom-up excavation sequences were considered, as well as the use of a temporary sprayed-concrete access shaft. As a result, the final design was sufficiently robust to allow subsequent programme saving initiatives by the contractor.

Construction sequence

The design of all structures is conditioned by the application and sequence of loads. A buried deep box structure supporting an OSD is no different. The main difference is that the loads are large. The assumed construction sequence therefore has a significant impact on the design of the structure.

The Western Ticket Hall was initially considered to be a top-down construction, like its neighbour the Goslett Yard Box in the east. The advantage of this method of construction is that the permanent works propping slabs are built as the excavation proceeds, providing stability and full support to the neighbouring ground, resulting in smaller settlements and less likelihood of damage to adjacent buildings. The initial designs were developed on this basis since the Western Ticket Hall sits in the middle of a dense urban environment of mainly old buildings, many of them listed. There was also sufficient time in the programme to substantially complete the box in a top-down sequence before the TBM for the eastbound tunnel drive (christened Phyllis) bored through the diaphragm wall and passed through the box.

However, the redesign of the Western Ticket Hall for the Government's Comprehensive Spending Review in late 2010 left insufficient time to complete the design, tender the work and build the box in a top-down sequence before Phyllis arrived in early 2013. Furthermore, there was not enough time after completing the tunnelling works to construct the whole of the Western Ticket Hall. It was therefore necessary to find a way to build a substantial portion of the Western Ticket Hall before Phyllis arrived.

This led to the adoption of a bottom-up construction sequence. This method utilises temporary propping to support the perimeter diaphragm walls while the excavation to formation level proceeds. The diaphragm walls were quickly redesigned to account for the installation of temporary props and waling beams during the excavation phase. This allowed for an early release of tender information for the diaphragm walls, temporary props, piles and raft while the detailed re-design of the internal propping slabs continued. The relatively unobstructed excavation was completed quickly in only six months, providing sufficient time to construct the raft before Phyllis arrived. The resulting shaft was one of the deepest open excavations ever constructed in central London.

The contract procurement was split into four phases at the Western Ticket Hall site:

- Starting in 2010, Site clearance and demolition was carried out by McGee under Contract C208.
- The foundations, including diaphragm walls panels and piles, were installed between May 2011 and January 2012 under Contract C421 by Balfour Beatty Morgan Vinci Joint Venture.
- The Western Ticket Hall box was excavated with temporary propping installed and the raft slabs cast under Contracts C300 and C410 by Bam Ferrovial Kier Joint Venture. The box was excavated in two stages. The deep section, through which the eastbound TBM passed, was excavated between May and November 2012, while the shallow section was excavated between March and May 2014.
- The internal structure of the station, plus the superstructure and ventilation towers at both eastern and western ends, as well as the building services and architectural fit-out of the station was carried out under Contract C422 by Laing O'Rourke, starting in May 2014 with most of the structure complete by the end of 2016.

The design team supplied an assumed construction sequence and a series of charts illustrating trigger levels for both temporary prop forces and diaphragm wall movements. The C300/410 contract under which the shaft was excavated monitored horizontal movements in the diaphragm walls using shape arrays and prop loads using strain gauges. Both monitoring methods gave 24/7 data gathered by data loggers which were reviewed at intervals throughout the day. The data were compared to the designer's charts to monitor behaviour of the walls and props.

Before excavation began, proposals were discussed between Contract C134, the contractor and Crossrail for the use of the Observational Method[5] to minimise the use of temporary propping. When the excavation sequence reached below –3 propping level, it was evident that the ground movements were less than predicted. C134's geotechnical engineers undertook a back analysis of the measured movements and produced updated charts for the remaining excavation stages, eliminating the entire lowest level of props[6].

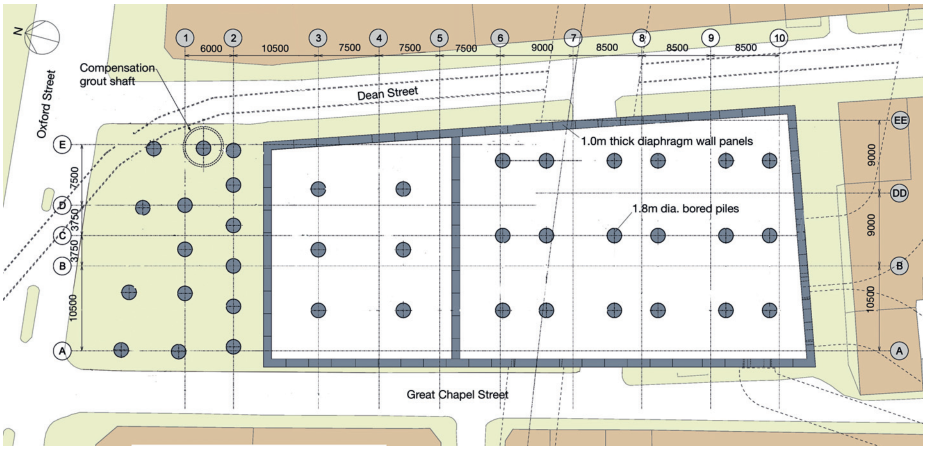

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Figure 21
Plan of Western Ticket Hall foundation piles and diaphragm wall panels

> **"THE RELATIVELY UNOBSTRUCTED EXCAVATION WAS COMPLETED QUICKLY"**

This proposal ensured that the base raft sequence was completed in time, eliminating the risk of delay to the TBM. Works for reception of the TBM included stitch drilling of openings in the diaphragm walls. The openings were temporarily filled with domed sprayed concrete-lined headwalls to form 'soft eyes'. The TBM's route between the two sides of the box was temporarily filled with foamed concrete so that the TBM could traverse across the box without the need for jacking frames and other works. Junk segments were erected through the station which remained until the TBM had completed its drive as the conveyors and ventilation were maintained.

The design of the temporary propping (Figure 22) was the responsibility of the C300/410 contractor; however, C134's design team looked at two indicative propping scenarios, an open transverse solution spanning across the entire excavation and a slender system utilising king piles at mid-span with bracing. The two indicative solutions provided a range of prop stiffnesses to the diaphragm walls. The indicative upper and lower stiffnesses were modelled using Frew to provide a range of prop forces for the contractor's temporary works design.

The indicative propping layout was distributed vertically to facilitate excavation of the box, removal of the props and construction of the permanent works in a bottom-up sequence. The design loads considered the construction loading during the build phase of works. These included a nominal impact load on a prop and the loss of any prop at any level. The prop-loss case had the greatest impact on the sizing of the waling beams, the purpose being to protect against progressive collapse of the excavation.

The C300/410 contractor elected to use the indicative open transverse propping arrangement which included muck-out access at each end of the site. Its design was modified to reflect the size of available tubing, lifting equipment and support arrangements.

Prior to the props taking up any load, selected members were identified for instrumentation; this included four strain gauges around the circumference of the tubing, at each end and at mid-span. The gauges were distributed at 45°, 135°, 225° and 315° around the circumference, rather than the more conventional 0°, 90°, 180° and 270°; while the gauges were protected, the selected distribution provided further protection against glancing blows. The gauges were calibrated, and initial strains checked when the erection support was removed. Thereafter, the gauges transmitted data 24/7 for review. The data were converted to axial loads and bending moments to check that the props performed as per the C134 designers' monitoring charts.

The waling beams were supported against a prepared surface on the diaphragm wall. The contractor elected to use shelf brackets rather than conventional gallows


Figure 22 View of temporary propping and raft slab construction

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brackets. The waling beam support was later developed into an embedded U-bar confined in the packing concrete between the waling and wall face.

The C134 designers' temporary works sequence had been included in the Category III independent check. While the design allowed for versatility in construction, the process and turnaround of changes added a restriction and risk to some of the contractor's proposals. An example of this constraint was a restriction on dig levels to comply with the check. The contractor wanted to excavate approx. 1m lower at the perimeter of the excavation to facilitate the installation of the shelf brackets. The restriction confined these reduced dig levels to pockets at the shelf location.

As mentioned earlier, the Observational Method was used to eliminate the lowest level of props. A consequence of this was that the excavation to formation for the raft required sequential excavation using hit-and-miss sequences with berms and a thicker blinding layer designed to act as a prop.

Interfaces with tunnels

There are four types of interface with tunnels at the Western Ticket Hall: running tunnel, platform tunnel, concourse tunnels and service tunnels (for MEP and ventilation).

As the Western Ticket Hall box existed before the tunnels, the design of waterproofing connections was generally the responsibility of the tunnel designer. Where a tunnel penetrates a diaphragm wall, the penetration is surrounded by an internal lining wall. The purpose of the lining walls is to transfer vertical loads around the penetration. They are all designed against hydraulic pressure should the diaphragm wall joints leak. Water tightness is provided by a drained cavity throughout.

The connection between the running tunnel and the lining wall is provided by embedding the tunnel segments into the lining wall. The joint is then reinforced with two hydrophilic strips around the circumference of the tunnel segments and a re-injectable grout tube to act as a fallback should the first line of defence be compromised. The boxes for the re-injectable tubes are located to be accessible from back-of-house areas.

The interface with the sprayed concrete-lined platform and concourse tunnels (Figure 23) is similar. The secondary sprayed concrete lining of the tunnels penetrates into the box to interface with the box lining walls. The tunnel designer developed a series of barriers of re-injectable grout tubes at the interface with the sprayed concrete lining and lining wall and around the annulus between the first-stage and second-stage concrete. The box designer introduced a confined flexible tape secreted inside a notch to provide a flexible waterproof membrane where differential movements are encouraged to occur. The tunnels are expected to become squat in time and will therefore move relative to the diaphragm walls. The notch introduces a crack inducer that is protected by the confined flexible tape, which in turn is supported by the secondary lining. Connections between tunnels and structures are notorious weak points and are therefore also provided with a drainage management layer which directs any future leakage to the station drainage system.

Back-of-house connections between sprayed concrete-lined tunnels and the box for tunnel ventilation and MEP service routes also have re-injectable grout tubes and drainage management systems.

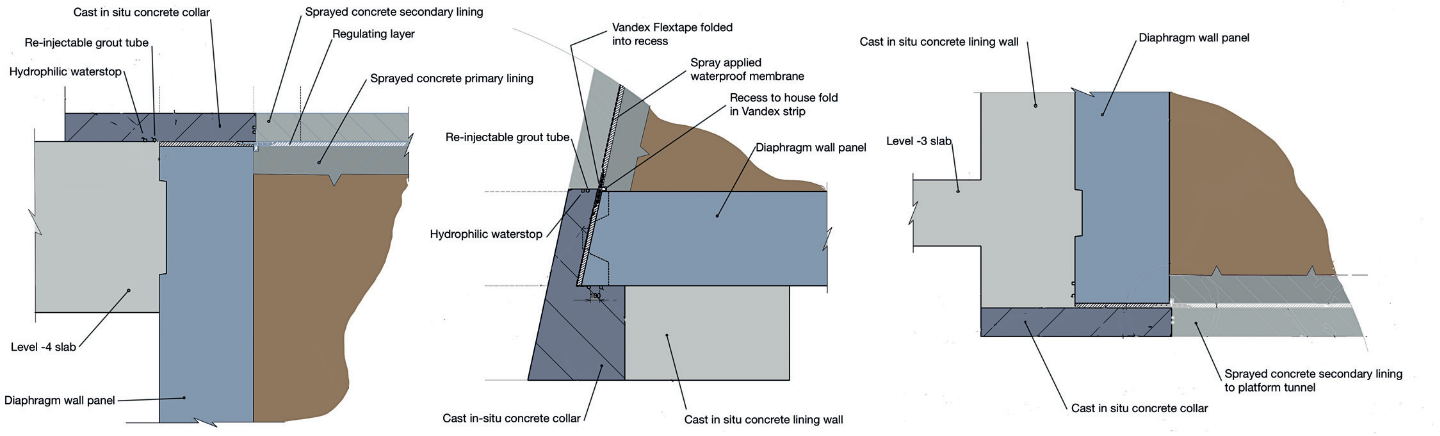
The design of connections is based on the assumption that the connections between tunnels and the box will most probably leak during the lifetime of the station; they are therefore provided with multiple layers of protection. Public areas have additional protection because water ingress into these areas would be poorly perceived, could damage architectural finishes and the access arrangements to these zones for remediation are more restricted.

The connections between tunnels and the station box are all within the London clay and large quantities of water are not expected from this source. However, when it does materialise it will have high pressure. The likely source of water will be down the external face of the diaphragm walls, which are within the surface deposit terrace gravels at high level. The connections are detailed to provide protection against water from either source.

Interfaces with Goslett Yard Box

The primary structure of the Goslett Yard Box was designed by Atkins under the London Underground contract for the upgrade of Tottenham Court Road underground station. However, the design of the ventilation tower from ground level

Figure 23
Section through connection between eastbound platform tunnel and Western Ticket Hall box at tunnel axis level



ARUP ATKINS

a) Invert level of platform tunnel

b) Axis level of platform tunnel

c) Crown level of platform tunnel

upwards remained part of Crossrail Contract C134. The design of the Goslett Yard Box, including the ventilation tower, had to be safeguarded for the construction of a future OSD. In this case, the planned development is for a mixed theatre and office building by Derwent London with Arup as structural engineers. It was necessary to agree a set of interface parameters between the three teams of structural designers at an early stage. These included agreeing a column grid, stability core and maximum loading. It was originally intended that stability of the OSD should be independent of the station. However, this proved impractical and it was decided that the ventilation tower would need to act as a stability core.

The OSD loadings were agreed in 2010 to allow the design and construction of the Goslett Yard Box to proceed in advance of the rest of the Elizabeth line station. In 2012, following design development, changes were made to the OSD loading requirements and positions. These required the introduction of additional transfer beams on the roof of the ventilation tower and additional analysis of the structure to ensure that the loading from the ventilation tower into the Goslett Yard Box, which by then was already under construction, was not exceeded.

Conclusions

The station has been successfully delivered to programme. At the time of writing, it is in the final stages of fit-out and is due to open in December 2018. The original vision for the design has been retained throughout the construction phase.

Coordination of the structural design with both the building services design and OSD continued during the construction phase.

A notable achievement during the construction phase of the Western Ticket Hall box was the use of the Observational Method to eliminate the lowest level of temporary props. This was made possible by the high quality of instrumentation and monitoring employed on the project.

Perhaps the most impressive achievement of the design was the degree of collaborative working between so many designers and contractors across so many interfaces. This proved especially challenging when dealing with contracts outside the Crossrail programme. Crossrail Ltd recognised very early that the success of the project depended on this working well. Its approach to co-locating design and construction teams, ease of communication between parties and well-controlled access to information made this possible.

Project team

Client: Crossrail Ltd
Project delivery partner: Bechtel, Halcrow, Systra
Civil and structural engineer: Arup Atkins Joint Venture
MEP engineer: Arup Atkins Joint Venture
Architect: Hawkins\Brown
Foundations contractor: Balfour Beatty Morgan Vinci Joint Venture
Excavation and tunnelling contractor: Bam Ferrovial Kier Joint Venture
Main structural works and station fit-out contractor: Laing O'Rourke

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FURTHER READING

►St. John A., Barker J., Frost S. and Harris D. (2017) 'Crossrail project: a deep-mined station on the Elizabeth line, London', *Proc. ICE Civ. Eng.*, 170 (5), pp. 47–56

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