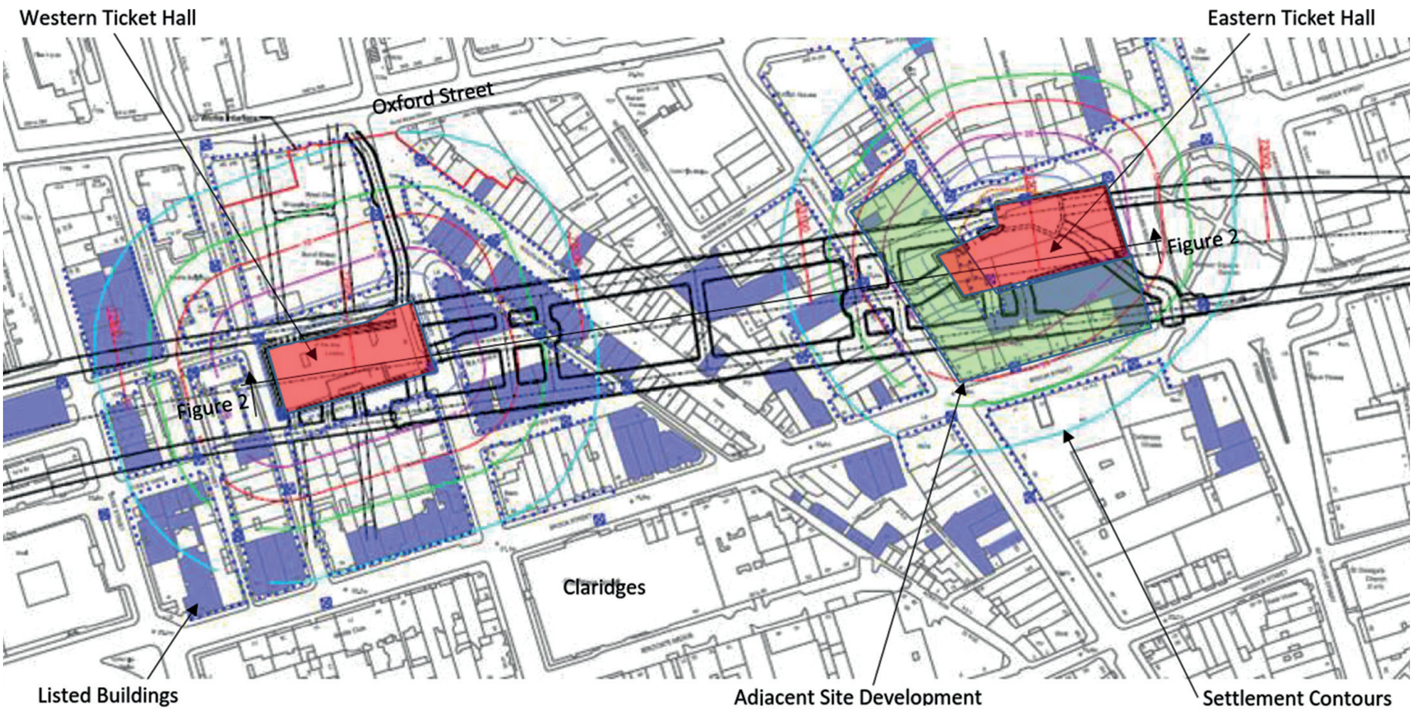
# Evolution of the design for Bond Street Elizabeth line station

Figure 1 Street plan with station overlaid

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**NOTATION**

| | |
|---|---|
| ASD | adjacent site development |
| CAD | computer-aided design |
| GFRP | glass fibre-reinforced plastic |
| GHS | GHS Limited Partnership |
| MEP | mechanical, electrical and public health |
| OSD | oversite development |

## Introduction

The design of Bond Street Elizabeth line station has evolved over 10 years of design and construction work. This article explains how the design has developed over this timeframe and how the independent designs for two clients were successfully delivered on the same site. It will discuss how the site constraints have informed the design, how the station was designed to be constructed and how it was ensured that the design has been assured throughout.

## Background

WSP was appointed by Crossrail Ltd in September 2009 as the framework design consultant for Bond Street Elizabeth line station. The station comprises two ticket halls in the centre of Mayfair connected together, some 35m below ground, by two 250m long platform tunnels (Figures 1 and 2). WSP was appointed to carry out the architectural and mechanical, electrical and public health (MEP) design through to RIBA Stage E[1], while developing the civil and structural design through to RIBA Stage F and construction status. As well as WSP, the design team included John McAslan + Partners as the architects and AECOM (then Scott Wilson) as the Category III checker, among others.

WSP was also the designer for the oversite development (OSD) and the adjacent site development (ASD) at the Eastern Ticket Hall. Here it was appointed under a separate contract with an independent design team to develop the design for the GHS Limited Partnership (GHS).

Due to the length of the project, the design has had to evolve to address the changing site and project conditions. Some eight years since the start of the commission, WSP is still employed as part of the site team to help deliver the construction.

## Design approach

The design team of around 150 full-time staff developed the design through to the end of 2012. The majority of the team was co-located with Crossrail at its offices and was able to develop the design in a truly collaborative fashion. The results of the team's design development each week would be pinned up on the wall on Friday afternoons for a critique session. These sessions allowed the whole team to understand how each discipline was developing and to comment on the direction the design was taking. This helped build and develop the team and ensured that the solutions developed were shared by the whole team. This collaborative process ensured the development of a robust peer-reviewed design.

Following the delivery of the architectural, structural and MEP design through to RIBA Stage E, the WSP team was retained to develop the civil and structural design further. The civil and structural design needed to

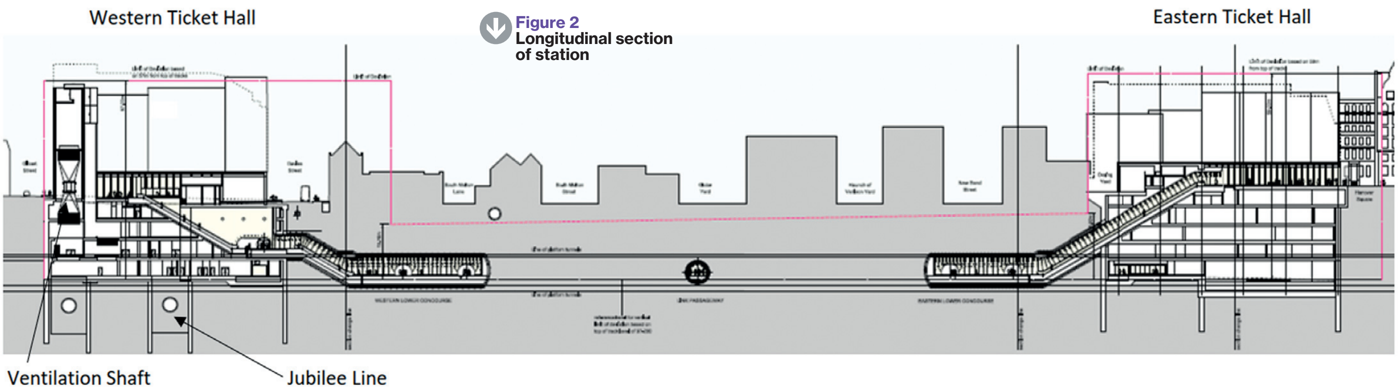



**Figure 2**
**Longitudinal section of station**

develop to RIBA Stage F and the production of construction information to allow early construction works to start on site. With the tunnel boring machines heading towards the station, the construction of the basement boxes needed to progress, incorporating early-access shafts for the tunnelling team as they came through the station.

## Design constraints

The station design was split into three main sections: the Western Ticket Hall, the Eastern Ticket Hall and the platforms. The two ticket halls both had a number of similarities: each was five-and-a-half storeys below ground to a depth of around 35m, and each also had to incorporate a ventilation shaft to allow the tunnel ventilation system (required to vent smoke in the event of a train fire) to extract above the proposed OSD. This system also allows the venting of air due to the 'piston' effect of the trains passing through the tunnels. Each ticket hall also included a podium deck to the first floor to allow for the siting of a future OSD of up to eight storeys, while providing permanent access from Day 1.

The detailed design of the OSD was to be carried out by the design teams of the developers; however, the programme for delivery of the OSD was considerably behind that of the station design programme. This was to be expected due to the long construction programme required to deliver the stations on site. In order to allow the station design to progress and the OSD to be space-proofed, the station design team developed a scheme design for both OSD sites. This design ensured the correct space provision for access and egress, welfare facilities, service routing, etc. to support the future operation of the OSD.

### Western Ticket Hall

Each of the ticket halls had its own specific design constraints which needed to be incorporated into their design. The Western Ticket Hall was constructed within a predominantly residential area and was constructed directly over the running tunnels of the Jubilee line (Fig. 2). It was constructed adjacent to a number of listed structures, each of which had very tight movement trigger levels placed on them as part of the undertakings and assurances process applied at the hybrid bill phase[2] of the Crossrail project. This limited the movement of some of the listed structures to 1–2mm when elsewhere this could have been in the order of 5–10mm for a similar structure.

In order to satisfy these requirements, a diaphragm wall construction was proposed for the external wall, to reduce the vibration arising from the installation. This approach was also possible due to the orthogonal nature of the ticket hall plan, aligned to the panel size of the diaphragm wall machine. This, supplemented with a compensation grouting system, allowed the project to meet the tight movement tolerances required here, for all stages of the construction works.

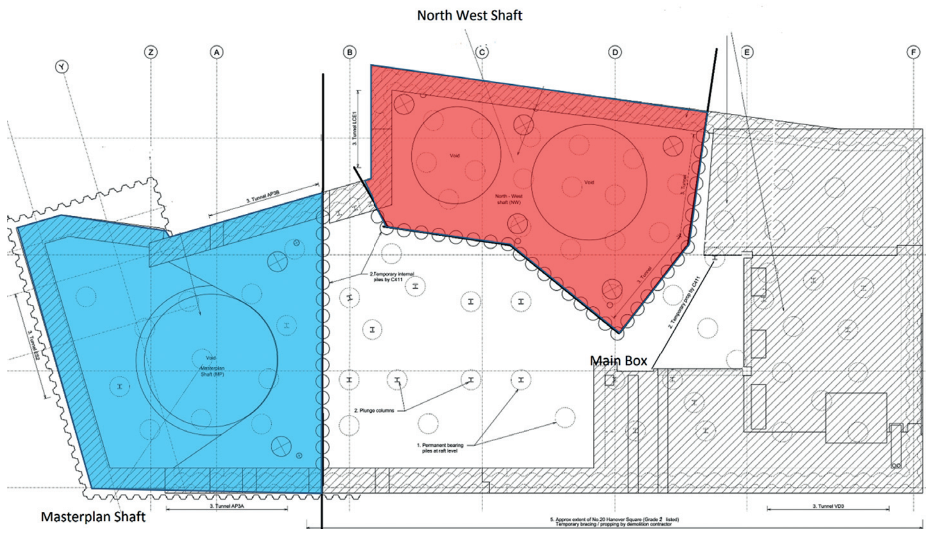



**Figure 3**
**Plan of Eastern Ticket Hall**

### Eastern Ticket Hall

The Eastern Ticket Hall is surrounded by an area of land owned by GHS which the company was in the process of redeveloping. Together with the development of the OSD to the Eastern Ticket Hall, this would complete a significant regeneration of the area. Two factors reduced the need to limit construction vibration, compared to the Western Ticket Hall, and allowed the design to employ a secant piled wall: i) the proposed development provided a sufficient stand-off distance to the residential properties in the area, and ii) the majority of the listed structures in the zone of influence were owned by GHS and formed part of the proposed development. The more flexible secant piled wall helped with the construction of the less regular perimeter of the basement to the station (Figure 3).

The ASD, which was part of the development by GHS, applied its own constraints on the design of the station basement box. The site which was to be developed consisted of existing masonry buildings of around five storeys in height; these were to be demolished to ground level, while the facades on New Bond Street were retained with significant temporary works. New basements were to be excavated adjacent to the external retaining wall of the station basement, followed by the construction of the new steel-framed and reinforced concrete buildings to form the final development.

The design of the station structure accounted for the top-down construction of two temporary shafts – the North West Shaft and the Masterplan Shaft – followed by the top-down construction of the rest of the station basement. The station also needed to be designed to account for the staged construction of the ASD. As the ASD was being developed to a separate programme, which Crossrail did not want to constrain, the station was designed to accommodate the staged construction of the ASD at any time during the construction of the station.

### Platforms

The platforms had fewer constraints due to the existing site conditions; however, they needed to be designed to accommodate a number of project constraints, such as high point loading to allow for the replacement of large pieces of plant via engineering trains and the use of glass fibre-reinforced polymer (GFRP) reinforcement to the platform nosing to ensure electrical separation from the track and the station earthing systems.

While the design of this was straightforward, utilising design guidance from the *fib* Model Code[3], the detailing of this section needed a lot of attention. Throughout the station the structure was designed for a 120-year design life. Over such a long period, it is reasonable to assume that other elements, such as the platform edge screens, would need replacement and that post-drilling into the platform would be required. The GFRP was therefore detailed in such a way that it could be located on site, even though it would not be picked up in a normal scan for ferrous reinforcement. As set out in Figure 4, sections of GFRP were placed to be exposed on the surface and aligned with the steel reinforcement further back in the span of the slabs.

## Design assurance

The design went through a vigorous verification process. Internally, it was regularly peer-reviewed and underwent Category I self-checking within the design team, and Category II checks by an independent WSP office. The design then went through an external Category III check by Scott Wilson (AECOM). This process ensured that the design was independently scrutinised and introduced a number of changes, predominantly in the assessment of the geotechnical parameters and their impact on the loading into the temporary works.

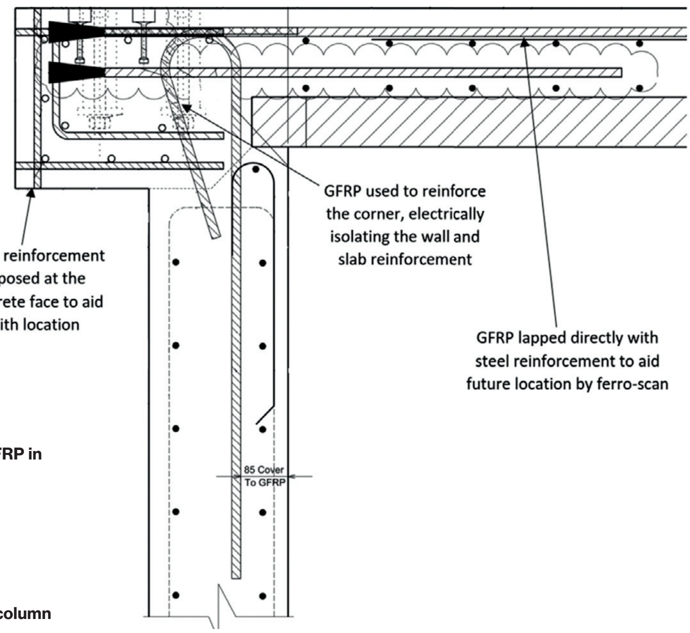



**Figure 4**
**Setting-out of GFRP in platform nosings**

**Figure 5**
**Collar to plunge column**

In addition to the verification works carried out by the design team, the design needed to pass through a staged-gate process with Crossrail. This required the provision of evidence to demonstrate that the design had been assured in line with Crossrail's procedures and coordinated with the other disciplines and at design/construction interfaces.

This high level of assurance continued through to the execution of the design on site. While the design-and-build contractor was appointed to be fully self-assured, Crossrail retained a site presence and assurance role with several full-time field engineers responsible for the sign-off elements of the works before they proceeded. This enhanced the quality control of the works constructed and reduced the number of non-conformances that occurred on site.

## Independent design teams

Subsequent to its appointment as the framework design consultant for the station development at Bond Street, WSP was appointed to design the OSD and ASD for GHS adjacent to and above the Eastern Ticket Hall. To enable WSP to deliver these works for two clients, two independent design teams were set up. As the majority of the design work for the Eastern Ticket Hall had recently been completed, it was possible to transfer across a number of key designers from the Eastern Ticket Hall team, with good knowledge of how the station design had been developed, to lead the development of the OSD and ASD design. This team was kept independent of the station design team, who were finalising the design and supporting the delivery of the project on site. This independence was important to ensure that no conflict of interest arose between the design teams.

The OSD and ASD design team was able to develop the design for GHS in a sympathetic fashion to the station design. This approach ensured that, while changes were proposed by the OSD to the station design, these changes were minimised and had already been assessed to enhance the likelihood of their acceptability to the station design. The OSD and ASD design was developed and adjusted alongside the finalisation of the station design to allow both schemes to be coordinated. This coordinated design was referred to as the masterplan scheme and provided benefits to both schemes, while adhering to the independence and differing assurance schemes required by both of the clients.

## Coordinating design changes

Two major changes to the schemes went through the change control process: the relocation of the ventilation shafts and the revision of the OSD column grids.

### Relocation of ventilation shafts

The original design for the station placed the vent within the main station and OSD footprint and acted to reduce its lettable area and efficiency. The ventilation shafts are also a source of noise and vibration, which can require significant mitigation to achieve suitable commercial space. To mitigate this, within the Western Ticket Hall the OSD design allows for isolated connections between the main frame and the ventilation shaft to overcome the noise and vibration transferring across to the main frame.

In the Eastern Ticket Hall, however, the design teams were able to work together with GHS to relocate these shafts from the OSD across to the ASD and to incorporate them within the less critical areas of the ASD accommodation, to mitigate issues with the transfer of noise and vibration. Moving the shafts across to the ASD section also increased the area available within the station basement box to locate one of the early-access shafts for the tunnelling contractor. This shaft was subsequently renamed the Masterplan Shaft to reflect this. The final location is shown in Fig. 3.

The change in the position of the ventilation shafts had significant benefits for both clients. For the OSD, it increased the lettable area of the development and removed the risk that an area of this would be affected by noise and vibration from the ventilation shafts. For the station, it allowed the positioning of the shafts in an area which caused less impact to the development of the station construction works.

The relocation did mean that large sections of each of the designs had to be reworked. For the OSD, the design team had to rearrange the accommodation in the ASD to allow for the positioning of the ventilation shafts, ensuring that the accommodation layout was positioned to suit the adjacency with the ventilation shafts.

For the station, the routing of the extracted air from the tunnel ventilation system needed to be revised to suit the position of the shafts. In this instance, the tunnel ventilation fans were relocated from a vertical position within a vertical ventilation shaft, to be positioned horizontally within the basement box. The two tunnel ventilation fans were positioned above each other on different floors and ventilation routes were spread through the station incorporating sloping sections of slab to transition through the levels.

### Revised column grid

The second major change was to the column grid for the OSD. As described above, the station was designed to accommodate an OSD which had been schemed by the station design team. This original design had allowed for the positioning of columns on a 9m grid from the podium level upwards. As the design for the OSD developed, it was requested that the columns move to a 3m grid around the perimeter of the building.

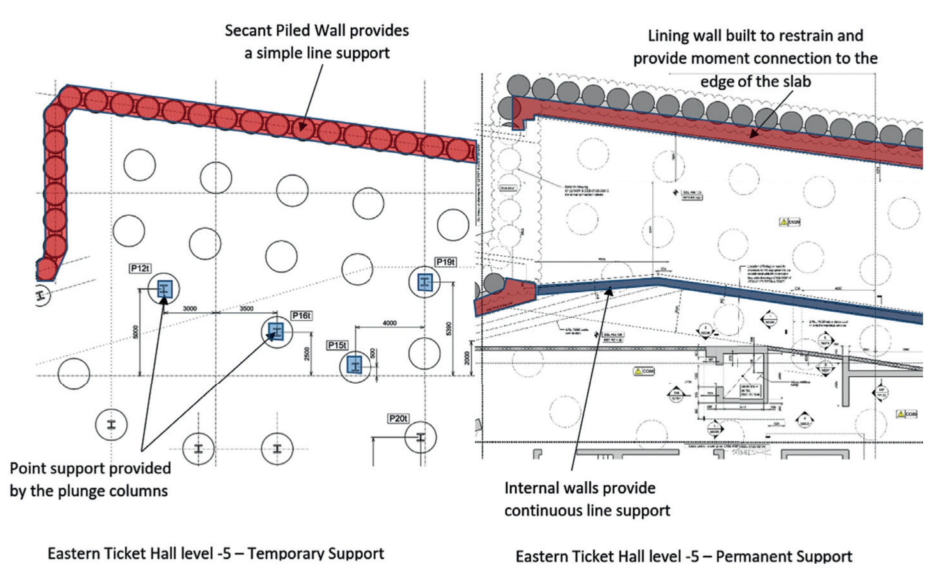
Working independently, the WSP team employed by GHS developed a revised design for the structure above the station podium deck. This design incorporated the revised external appearance of the OSD and allowed the transfer of load such that the load distribution and total load remained similar to that considered in the original OSD scheme design. This careful consideration reduced the amount of redesign required by the station design team.

The station redesign had to validate that the total load and the load paths remained largely unchanged and that there was no effect on the below-ground structure which had already been built. The work by the OSD design team meant that the review required to confirm this was limited. The changes were limited to the edge beams of the first-floor podium deck, which needed to be redesigned to pick up the intermediate point loads from the 3m column grid and to transfer these back to the main column grid at 9m centres.

The design of the reinforced concrete elements within the station was limited to a 0.3mm crack width to satisfy the Crossrail Civil Engineering Design Standards[4]. Two limits were applied for crack control across the project: 0.2mm for water-retaining structures and 0.3mm elsewhere to ensure the quality of the appearance. This design case governed for the design and detailing of these elements, while the ultimate limit state design was not significantly affected.

The revised design was then re-assured through the same rigorous process as the original design. Internal checks were carried out on the revised design prior to this being sent out for a revision of the independent external Category III design and recertification. Once the design was acceptable to both the WSP and AECOM design teams, the changes were presented back to Crossrail under a 'gate impact report'. This impact report was produced to demonstrate that the revised design had undergone the same level of verification as the previous design and that the revisions did not impact on the coordination with any of the other disciplines, which had been demonstrated to Crossrail through the staged-gate review process.

**Figure 6**
**Temporary and permanent connection to secant piled wall**



## Design to construct

While every structure needs to be designed with construction in mind, the construction of this station in the centre of Mayfair required a thorough understanding of the processes that could be utilised. Construction advisers were an integral part of the design team and were able to deliver a number of solutions to achieve this. These varied from the sequential installation of the precast concrete coffer units for the first floor of the two ticket halls, to achieve the ±3mm architectural tolerance, through to the performance specification of a propping system to be installed in place of the permanent slabs where these sloped between floors.

The station boxes had been designed to be built on constrained sites and in a top-down construction sequence. This sequence required the ground-floor slab to be designed for a number of design loading conditions as a construction deck: firstly, as a staging ground for the piling and diaphragm wall works, followed by the staging for the excavation of the basement box in a top-down sequence. For the Eastern Ticket Hall this was also staged into three elements: the North West Shaft, the Masterplan Shaft and the main box.

To construct the basement boxes in a top-down fashion, the main elements needed to be designed to work in a number of temporary conditions. The Eastern Ticket Hall box was designed to be excavated in sections and supported in a temporary condition with the early installation of the Masterplan Shaft, followed by the early installation of the North West Shaft which was infilled with the permanent structure at the same time as the top-down construction of the main box. The basement box would then be finished with the top-down permanent slab construction in the Masterplan Shaft. These sequences were considered in the development of the original design and were incorporated in the design of the structure.

## Top-down construction

The top-down construction was enabled by the installation of plunge columns. These were installed with the piling from ground level: when the piles were concreted to the underside of the lowest-level slab, the plunge columns were lowered through the empty core and founded into the concrete, with regular spacers around the columns to ensure their verticality. The core was backfilled around the plunge columns to ensure that they were stable in the

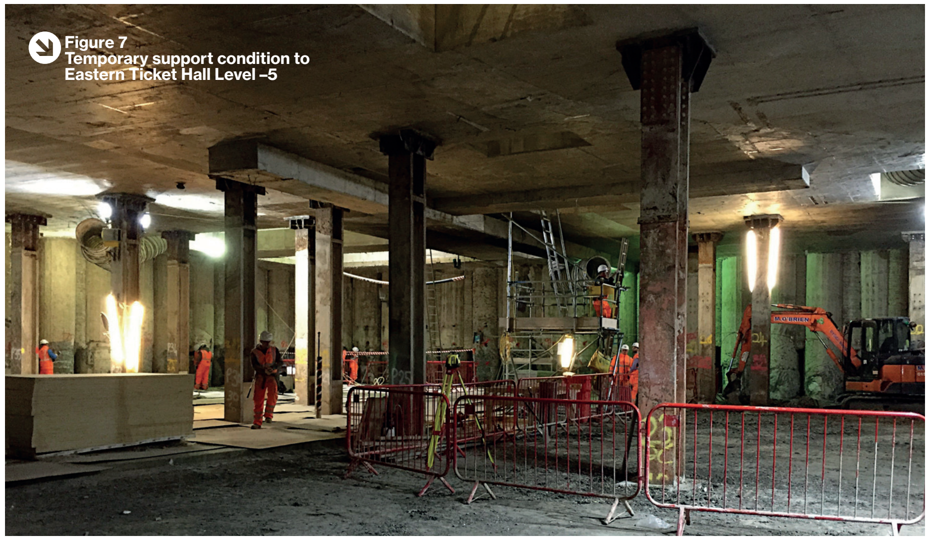


Figure 7
Temporary support condition to Eastern Ticket Hall Level –5

temporary condition, as they were then re-exposed during the top-down excavation works.

The permanent slabs were constructed on the excavated base at each stage of the excavation works. Collars were installed onto the plunge columns (Figure 5) at each of the floor levels to reduce the impact of punching shear effects at the connections between the floor slabs and the columns. This provided point supports to these slabs internally. The slabs were connected to the external secant piled wall, connected into couplers installed within the piles as they were originally cast. These connections provided a simple support condition to the edge of these slabs. In the temporary condition, a series of mole holes was provided within the slab to allow for construction access through the station box from ground level.

Once the excavation had been completed to the lowest level, it was possible to start the construction of the permanent vertical loadbearing structure in a bottom-up sequence. The permanent loadbearing structure comprised an inner skin and lining

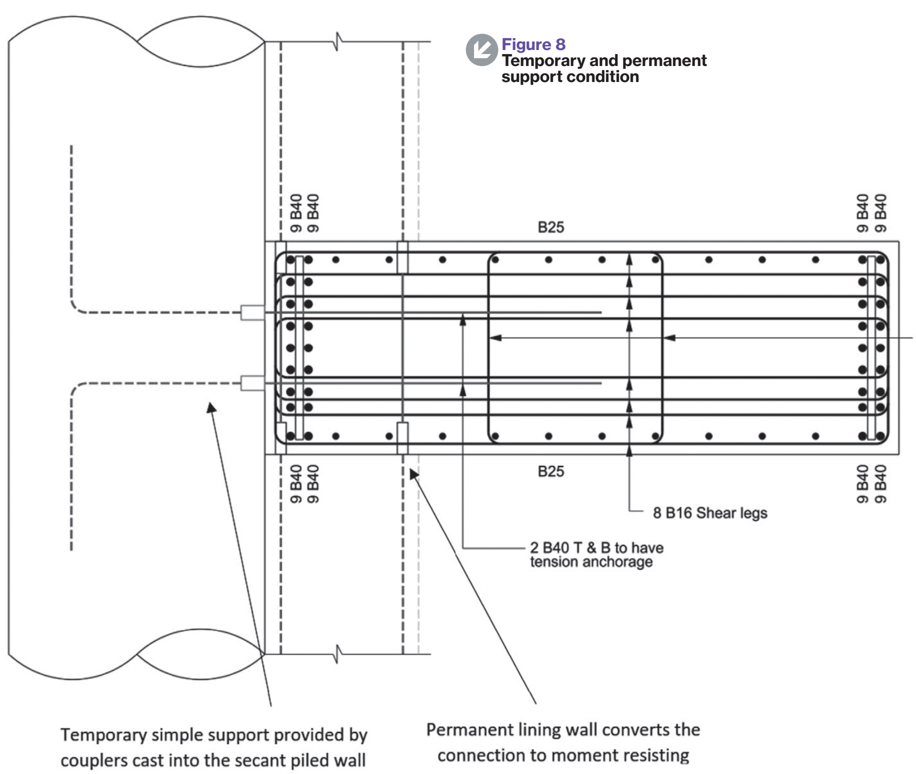



Figure 8
Temporary and permanent support condition

wall to the external piled walls; the lining wall was approx. 700mm thick, plus an allowance for tolerance, and was detailed to be continuous through the structural slabs, which had already been cast, via coupled bars through the slab, installed as part of the top-down sequence.

Internally the structure was supported by loadbearing walls generally, with a small number of columns. This permanent condition changed the support to the structural slabs from localised point supports internally and a simple support to the edge of the slab, through to a series of internal line supports onto reinforced concrete walls and an external moment connection into the lining wall (Figures 6 and 7). This increase in the support condition in the permanent case allowed an increase in the load capacity of the intermediate slabs from around 5kPa in the temporary case to a total of 15–20kPa in the permanent case, as a combination of superimposed dead load and live loading (Figure 8).

Once the permanent vertical loadbearing structure was in place, it was possible to remove the plunge columns. The post-installed collars to the plunge columns were removed and the localised grout packing around the columns at the floor levels was broken out. This allowed the plunge columns to be extracted vertically through the slabs to ground level.

Figure 9 Propping to waling beams on secant piled wall

## Temporary works and monitoring

Significant temporary works were required to facilitate the top-down construction sequence. Typically, these employed sections of the permanent works acting in a temporary condition, but this wasn't always possible. In such locations, waling beams were designed into the lining wall construction to allow the secant wall to be propped back to the main structure, typically at grid lines. These props were designed to support loads of up to 11 000kN, as an output of the analysis of the soil–structure interaction (Figure 9).

This interaction was subject to a degree of assumption in the development of the design and the accuracy of this was integral to the stability of the basement box in the temporary condition. As such, it was important to confirm that the assumptions included within the design were correct, or conservative. In order to achieve this, a monitoring regime was specified and installed within the embedded retaining walls to record the actual movements of the structure in operation. This consisted of a series of cast-in inclinometers and discrete monitoring targets, combined with trigger levels set at amber, red and black levels. A breach at any of these levels would trigger progressively more stringent limits on the progression of works, combined with additional monitoring requirements to ensure the safety of the structure.

Monitoring periods were set weekly, increasing in frequency during periods of excavation or de-propping where movement was expected. An example of the output of this monitoring is shown in Figure 10; the amber trigger levels were not breached.

## Site support

The appointment as framework design consultant included provision of engineering support on site during the construction phase of the project. WSP provided a site team of up to 15 engineers and CAD technicians to fulfil this role. This team primarily responded to queries raised by the construction team and by the contractor's architectural and MEP designers who were developing their detailed design. This support role involved answering technical queries, as well as revising the design and construction details of the structure to accommodate the changing architectural and MEP design and the preferred construction methods of the contractor. The majority of the design changes involved minor changes to the structure, incorporating builders' work openings and changes to upstands to suit the development of the services distribution and the clarification of cladding details.

A number of more significant changes arose during the construction phase. The most significant of these was the revision of the construction sequence to the Masterplan Shaft. While the permanent slabs in the area of the other early-access shaft, the North West Shaft, were constructed early during the top-down construction of the main box, the Masterplan Shaft was left open to facilitate easy access to the platform level for the main contractor and the other system-wide contractors so that they could complete the platform and track works. This placed the infilling of the Masterplan Shaft with the permanent structure onto the critical path towards the end of the project.

To support the construction of the rooms and service routes to the lower levels of the basement box first, a revised sequence was proposed to infill the permanent structure to the Masterplan Shaft in a bottom-up sequence. The revised sequence imposed a significantly different construction sequence onto the external piled wall within the Masterplan Shaft corner. Originally the permanent slabs would have been installed prior to the demolition of the first of the temporary slabs, serving to enhance the support to the external wall as the works progressed. With the bottom-up sequence, the temporary slabs needed to be demolished prior to the installation of the permanent slabs to ensure that there was a suitable route for the removal of the demolition arisings. To enable this alternative support system to work sufficiently with the existing, as-installed, piled retaining wall, a system of additional temporary works was required to support the piled wall and to ensure that it did not deflect during the infilling of the Masterplan Shaft.

## Designed for an evolving design

The architectural and MEP design of the station has been progressing several years behind the civil and structural design. This has meant that key interfaces between the disciplines, such as builders' work openings and secondary support structure for the cladding, have been finalised after much of the structure has been constructed. This was allowed for in the original design by ensuring that there was some scope for later change.

Instead of a 0.99 utilisation ratio, the design was typically carried out with a utilisation ratio of 0.9–0.95 to balance the need for an efficient design with scope for future flexibility. This allowed new builders' work openings to be introduced in most of the areas in which they were requested. Similarly, the partition allowances that the team included as part of the superimposed dead load allowance were sufficient to allow medium-dense blockwork walls to be adjusted to *in situ* reinforced concrete walls, to allow for the omission of a secondary steelwork sub-frame to the cladding.

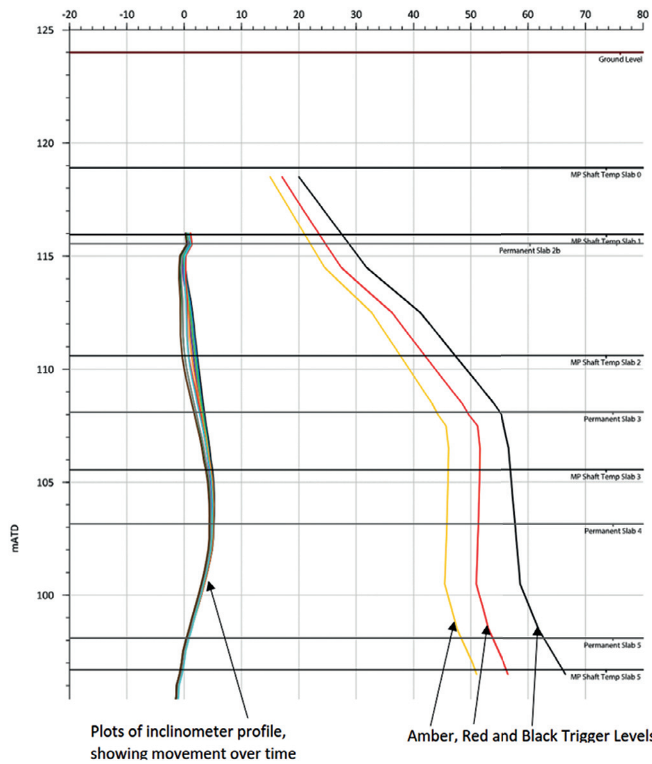
As part of the role on site, WSP has worked closely with Crossrail, the client, and with Costain Skanska Joint Venture, the contractor. The parties collaborated to ensure that the works on site progressed to programme while ensuring the quality of the work would not be affected. Part of this work included ensuring that the site team knew the importance of the constraints placed on the construction sequence. This was achieve through regular meetings with the contractor's engineering and temporary works teams, and lunchtime sessions where a joint team presented the importance of the temporary works systems to the contractor's office and site teams. This briefing programme was coordinated to align with the works on site to keep it relevant.

## Summary of key points

A number of lessons were learned by the design team and have been captured by Crossrail to be taken forward to other projects as a learning legacy. Those that particularly stand out on this project are presented below:

- **Design to construct** – everything needs to be built and it is a designer's responsibility to ensure that it is possible to build safely what has been designed. At Bond Street this included the incorporation of elements of temporary works within the permanent structure of the station, reducing the need to install and remove temporary works.
- **Design for change** – with a project lifecycle of more than 10 years it is inevitable that there will be change. It is also unlikely that all the changes over this timespan could be predicted at the outset of the project. Given this and the difficulty in altering a deep basement, designing in spare capacity as part of the structural design was considered more sustainable and cost-effective than designing to the limit and having to rebuild elements later.
- **Focus on interfaces** – interfaces are the locations where misunderstanding or scope gaps are likely to arise. Ensuring that these are agreed and developed in parallel between the design parties across the interface, as early as possible, will save the designers and contractors time and effort further into the project. Across the Crossrail project, interface control documents were used to document the agreements and were kept as live documents that were updated as the design and construction progressed.

**Figure 10**
**Typical plot of movement against trigger levels**




## Project team

**Framework design consultant:** WSP
**Client (station):** Crossrail Ltd
**Client (OSD and ASD):** GHS Limited Partnership
**Architect:** John McAslan + Partners
**Category III checker:** Scott Wilson (AECOM)
**Contractor:** Costain Skanska Joint Venture

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