

Innovative engineering to control Big Ben's tilt

Design and construction of the Jubilee Line Extension for London Underground created many exciting engineering challenges. Not only were there 10 km of twin tunnels, crossing the River Thames in 4 places, and 11 new stations to be built (8 of which were underground), but many buildings had to be protected from potential damage caused by settlement. Probably the most sensitive of these buildings was the Big Ben Clock Tower at Westminster. The construction of the new Westminster Station and tunnels was predicted to produce significant movements of Big Ben and the adjoining Palace of Westminster. This article describes how the innovative technique of compensation grouting was adopted to control the tilt of Big Ben during construction of Westminster Station and the new tunnels.



Westminster Station

The deepest excavation ever undertaken in London was for the new Westminster Station and Jubilee Line Extension tunnels. The location and layout of the station in relation to Big Ben is shown in plan in Figure 1 and section in Figure 2. The main excavations required to form the station comprised a 39 m deep excavation between reinforced concrete diaphragm walls (known as the station box) and two vertically stacked 7.4 m diameter platform tunnels constructed between

the station box and Big Ben. The north edge of Big Ben is only 28 m from the centre line of the tunnels and 34 m from the diaphragm walls of the station box.

Diaphragm walls are a technique commonly used to support the sides of deep excavations in urban areas. They are constructed by excavating deep slots in the ground, typically about 1 m x 4 m in plan, temporarily supporting the sides of the excavated slots with a thick mud, lowering a cage of steel reinforcement into the slot, and then

filling it up with concrete from the bottom. This results in a reinforced concrete wall constructed in the ground (typically about 1 m in thickness).

The new station box is located directly beneath the New Parliamentary Building (now known as Portcullis House), which provides accommodation for MPs. The station box provides the ticket hall for the station, access to the platform tunnels via escalators, and interchange facilities with the District and Circle Lines.

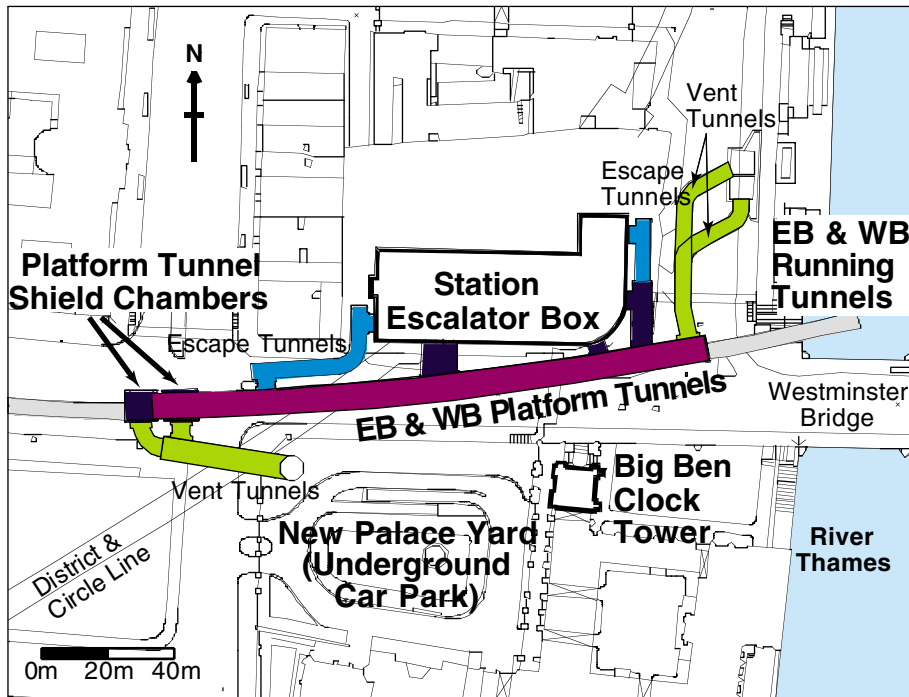


Figure 1: Plan of the new Westminster Station and Jubilee Line Extension tunnels.

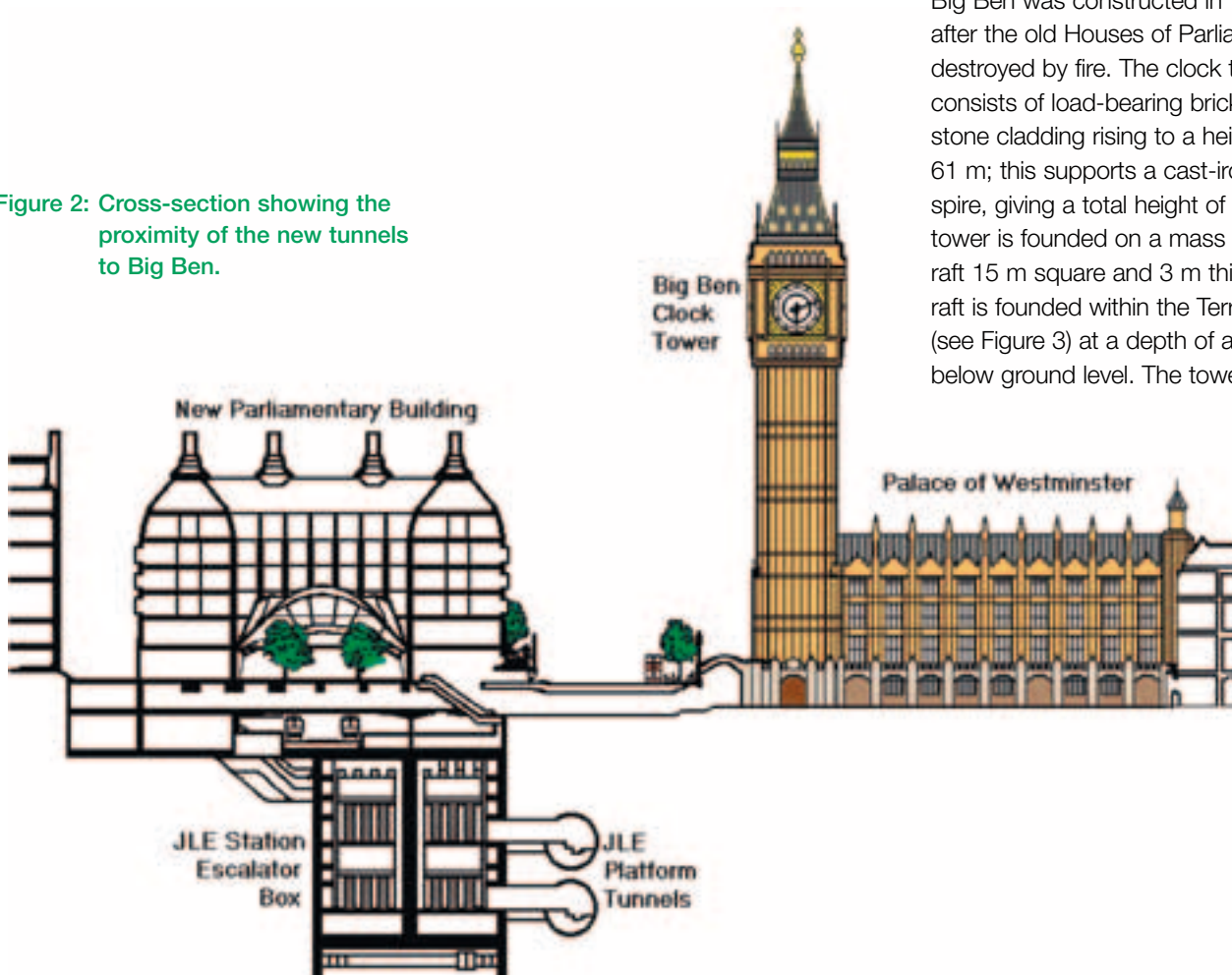
Design of the station box had to meet the following exacting criteria:

- Provide support to the overlying Portcullis House, itself a seven storey building.
- Allow for headroom constraints that required the District and Circle Lines to be lowered in order to allow street-level access to Portcullis House.
- Provide new ticket hall and interchange facilities with the District and Circle Lines.
- Provide sufficient space for new escalators to give access to the new Jubilee Line Extension platform tunnels.
- Ensure that the combined settlement effects of the construction of the station box and the tunnels did not result in unacceptable movement of adjacent structures, in particular of Big Ben.

Big Ben Clock Tower

Big Ben was constructed in 1858, soon after the old Houses of Parliament were destroyed by fire. The clock tower consists of load-bearing brickwork with stone cladding rising to a height of 61 m; this supports a cast-iron framed spire, giving a total height of 92 m. The tower is founded on a mass concrete raft 15 m square and 3 m thick, and the raft is founded within the Terrace Gravels (see Figure 3) at a depth of about 7 m below ground level. The tower is

Figure 2: Cross-section showing the proximity of the new tunnels to Big Ben.



estimated to have a weight of 85 meganewtons, giving an average bearing pressure on the underside of the raft foundation of about 400 kilopascals.

Ground conditions and movements

A cross-section through the station box, the tunnels and the foundations of Big Ben is shown in Figure 3, which also shows the soil strata. The Terrace Gravels (on which the mass concrete raft of Big Ben is founded) are about 6 m thick and are underlain by London Clay which is about 35 m thick and extends to below the bottom of the station box.

Any deep excavation in soft ground inevitably causes ground movements outside the excavation. Vertical ground movements lead to settlement of adjacent buildings and possible damage (depending on the magnitude of the movement); this is usually accompanied by horizontal ground movements which can also cause damage in some circumstances. The magnitude of ground movements is directly proportional to the depth of the excavation, and the extent to which

ground movements are detected is typically around twice the excavation depth (from the edge of the excavation). Construction of the 18 m deep New Palace Yard underground car park (see Figure 1), which is 16 m to the west of Big Ben, caused the tower to tilt towards the car park by about 1:4000. Hence the presence of Big Ben only 34 m from the edge of the 39 m deep excavation was definitely a cause for concern.

The problem was compounded by the proposed construction of the two platform tunnels between the station box and Big Ben. Tunnels in soft ground also cause settlement and horizontal ground movements. Analysis showed that the combined construction of the station box and tunnels would cause Big Ben to tilt towards the station by a significantly greater amount than it had moved towards the underground car park, unless protective measures were implemented.

Preventing the tilt

The tilt of Big Ben towards the station needed to be carefully controlled

because of the intimate connection between the tower and the Palace of Westminster – tilt would lead to cracking where the tower and the Palace were connected. Particular measures incorporated into the design of the station box to minimise ground movements included stiff walls and internal propping of appropriate stiffness, and low-level tunnelled struts installed before excavation.

The location of the struts is shown in the cross-section in Figure 3. Three tunnels of 1.7 m diameter were excavated by hand in the London Clay; access was gained from the open shaft of one of the 3 m diameter shafts used for the piled foundations to support the station floors and the overlying Portcullis Building. Each tunnel was then filled with concrete, and jacks installed so that the load in the struts could be adjusted as the excavation proceeded within the main station box. Finite element analysis had shown that these low-level struts installed prior to any excavation within the station box would significantly reduce the ground movements by restraining the

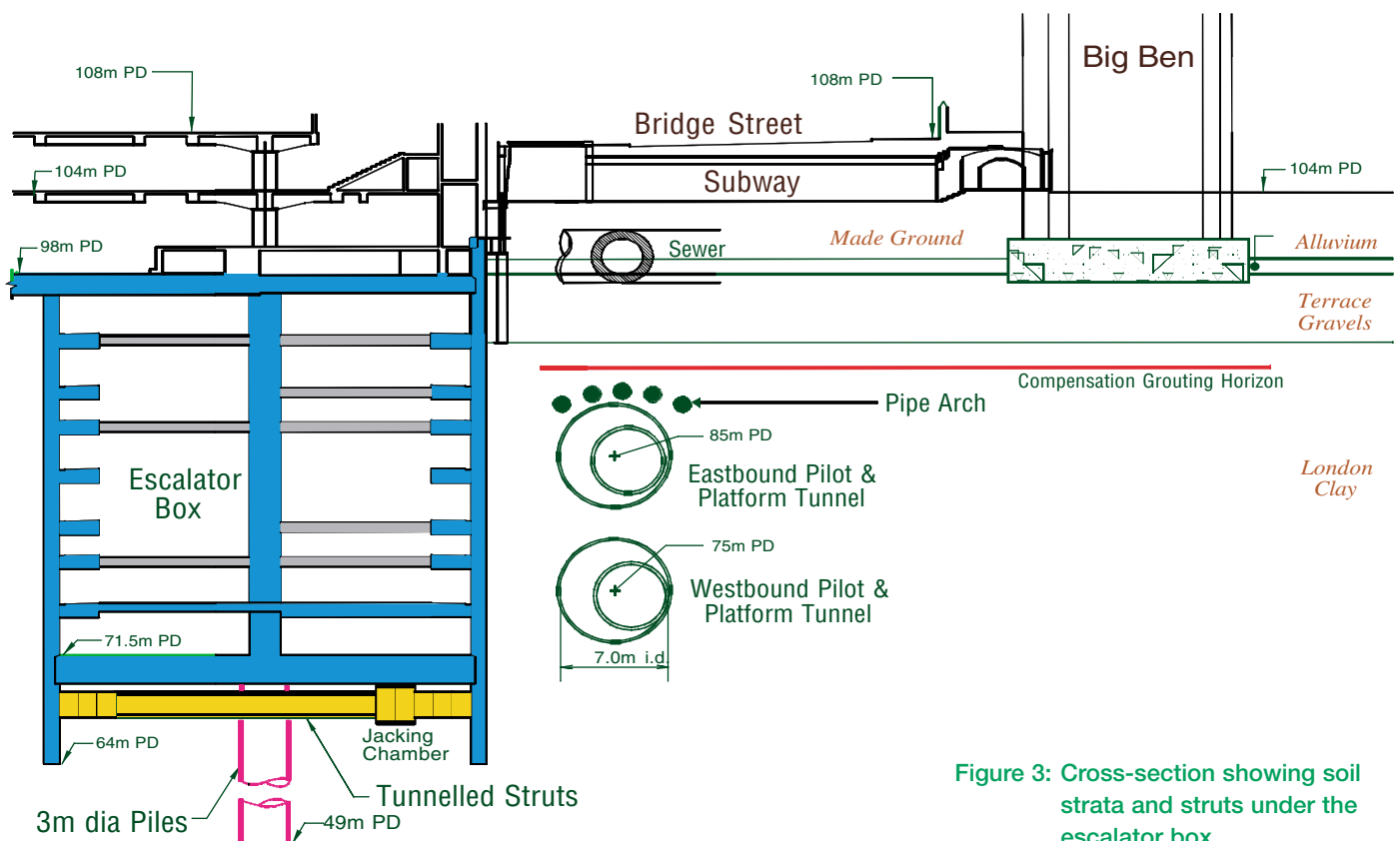


Figure 3: Cross-section showing soil strata and struts under the escalator box.

diaphragm walls from moving inwards during excavation.

Despite the provision of the low-level tunnelled struts it was recognised that the combination of the station box excavation and construction of the two 7.4 m diameter platform tunnels would still lead to unacceptable tilting of Big Ben. Another contingency protective measure was called for.

Compensation grouting

Compensation grouting is a relatively new technique for controlling ground movements induced by tunnelling and deep excavations. It was first introduced in the UK to control settlements during construction of a 10 m diameter escalator tunnel beneath Waterloo Station and the technique was subsequently widely adopted on the Jubilee Line Extension project. The principle of the technique is to inject grout (a mixture of cement, sand and

water) between the tunnel and the affected building's foundations to compensate for the ground movement caused by the tunnel excavation.

The grout is injected simultaneously with tunnelling in response to detailed monitoring observations, the aim being to limit building settlement and distortion to specified values.

To achieve this, a network of horizontal steel tubes is installed in the ground beneath the structure to be protected. Each tube (known as a TAM, the abbreviation for 'tube à manchette') has a series of holes, typically spaced at 0.3 m intervals. A system of rubber sleeves and inflatable packers is used to select a particular hole through which grout is injected, and the system allows repeated grouting through the same hole.

Figure 4 shows the array of horizontal grout tubes drilled from a shaft which was located in the middle of Bridge Street. The tubes were about 50 m long and were drilled beneath the foundation of Big Ben and immediately to the north. The level of the tubes was chosen to be just below the interface of

the Terrace Gravels and London Clay (shown in Figure 3 as 'Compensation Grouting Horizon'). The spacing of the tubes was designed to allow grout to be injected from any one of a very large number of holes.

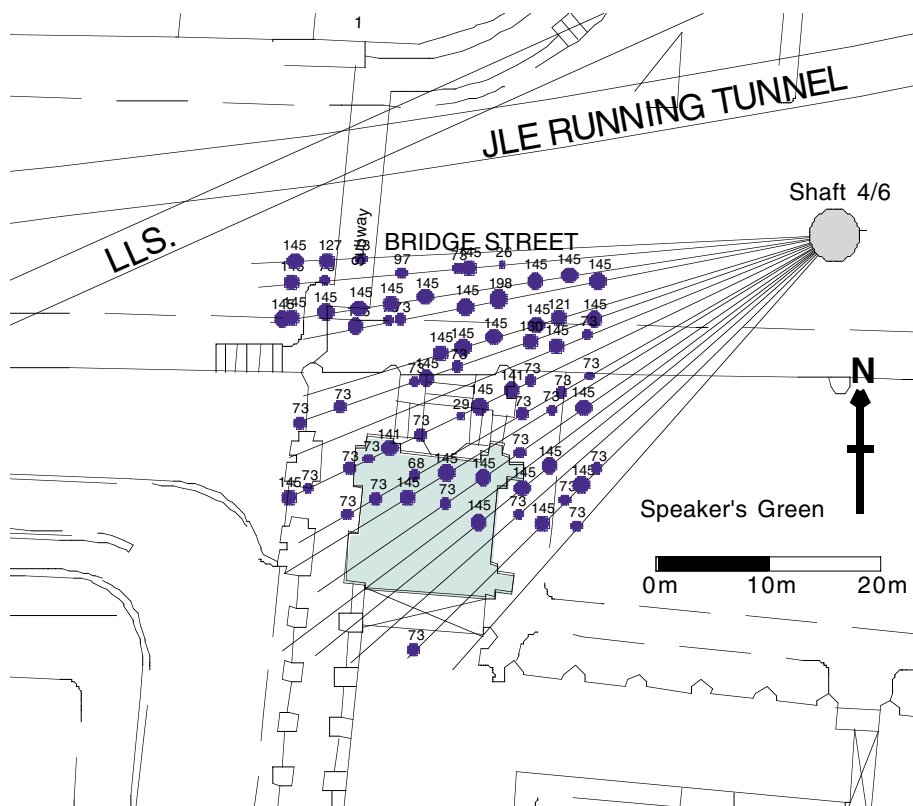
The decision as to which hole, and how much grout, to use depended on the detailed response of Big Ben to the construction of the adjacent station and tunnels. The grouting aimed not to stop all tilting but to prevent Big Ben from tilting more than an acceptable amount. Grouting was undertaken over a 21-month period, from January 1996 until September 1997, during which a total of 122 cubic metres of grout was injected in 24 different episodes. The pattern of injections used most frequently is shown in Figure 4, and the solid circles represent the quantity of grout (in litres) injected for a particular episode.

Measurements

The tilt of Big Ben was the most important parameter that had to be monitored during the station and tunnel construction, and a range of independent monitoring systems was installed. An optical and an electronically read plumb line were used to measure tilt directly – the electronic data being transmitted immediately to computers in the engineers' offices. Prism targets attached to the clock faces were surveyed to give displacements in three dimensions, and precise levelling of 4 points was undertaken on the corners of Big Ben; from these measurements the tilt could be calculated.

Figure 5 shows the observed change of tilt with time as the deep excavation for the station progressed and the tunnels were constructed. The tilt is represented as the horizontal movement at a height of 55 m, which corresponds to the height of the clock face above ground level. Along the top of Figure 5 can be seen the tunnel progress (comprising pilot tunnels and then enlargements), and along the bottom of the figure can be seen the station box excavation progress (in metres, up to 39 m in depth).

Figure 4: Array of grout tubes showing the most frequently used pattern of injections (solid circles represent quantity of grout in litres).



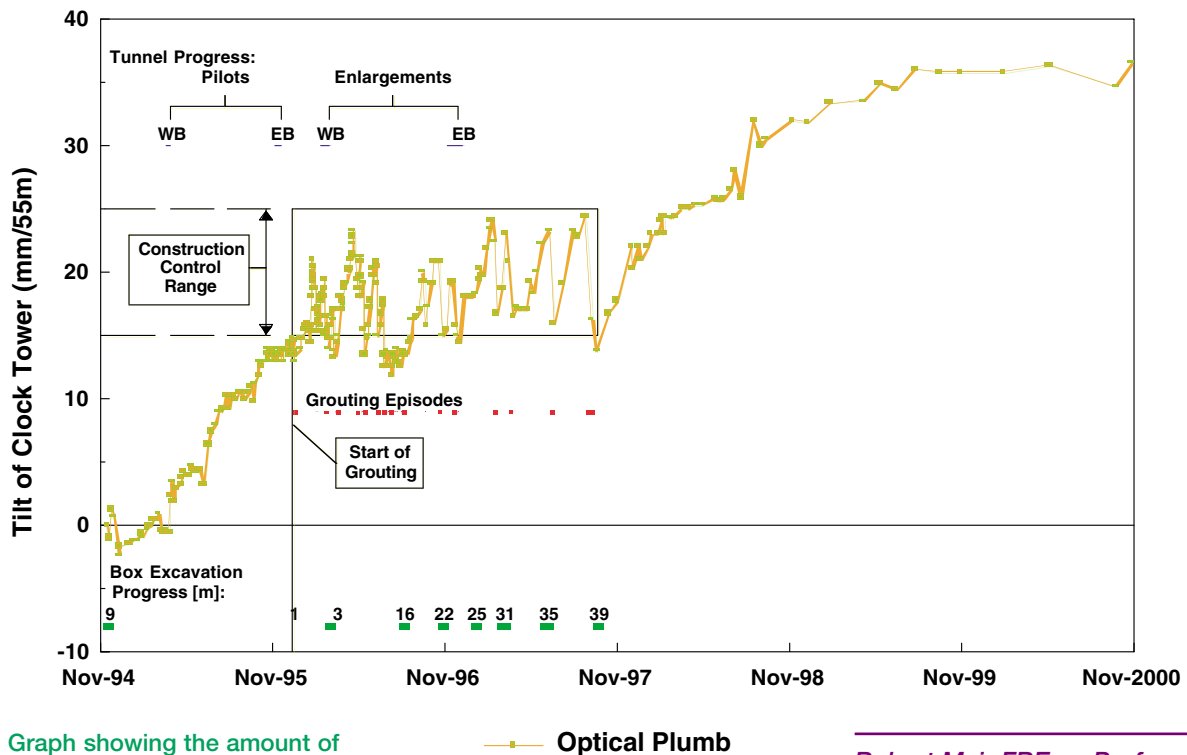


Figure 5: Graph showing the amount of horizontal movement of Big Ben at clock face level from 1994 to 2000.

During construction it was stipulated that Big Ben's tilt should be controlled to be in the range 15–25 mm. A trigger level of 15 mm was established at which compensation grouting would have to commence. This was reached in December 1995. During the next 21 months, until September 1997 when the deepest level of the station excavation was reached, grouting was undertaken to restrict the tilt within the specified range, and it can be seen from Figure 5 that this was generally achieved. By careful attention to the monitoring data, it was possible to maintain control within fine tolerances by adjusting the volume of grout injections required and carefully determining the points of injection.

Without any compensation grouting the cumulative increase in tilt of Big Ben by the end of construction of Westminster station and tunnels would have been at least 120 mm. This would certainly have been unacceptable because it would have resulted in significant cracking of the historic Palace of Westminster.

Final results

Since the end of construction, no further grouting has been undertaken. It can be seen from Figure 5 that appreciable time-dependent tilt has continued to take place in the 3 years following completion of the station. This is a result of the London Clay swelling and consolidating, as the water pressures within it respond to the new regime and adjust to their long-term equilibrium values. This is consistent with computer predictions and is still being monitored very closely – the measurements indicate that the long term tilt has almost stabilised at around 35 mm.

The innovative technique of compensation grouting, which has never before been applied to a structure as fragile and of such historic importance as Big Ben, has been extremely successful and is a great credit to the contractor, Balfour Beatty / AMEC. In combination with a number of very accurate systems of monitoring the tilt, the technique has resulted in Big Ben being prevented from leaning and damage to the Palace of Westminster has been avoided. ■

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David Harris is a Chartered Engineer; he joined the Geotechnical Consulting Group in 1989, becoming a Director of the company in 1995. He was seconded to the Jubilee Line Extension Project Team between 1994 and 1998 as a specialist geotechnical advisor with a particular responsibility for settlement-related issues in the Waterloo and Westminster areas.



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