Twenty-one years of heave monitoring in London Clay at Horseferry Road Basement

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Abstract

An 11 m-deep basement structure in London SW1 was left vacant from 1968 to 1989. The basement heaved significantly during this period due to the lack of a superstructure, providing a unique opportunity to study the development of long-term heave in London Clay. May (1975) presented the monitoring results from 1968-73 and excerpts of site data collected after 1973 have also been circulating informally in the industry since the 1990s. However, the full set of monitoring data remains hitherto unpublished.

This paper was initially drafted in the early 1990s when three of the authors (Nicholson, Chapman, and Solera) were working together with Arup. The paper somehow never got published as people and circumstances changed. More recently, the first author (Chan) started postgraduate research on heave and pressure beneath slabs in excavations in over-consolidated clays, using the heave monitoring data from the draft paper to complement centrifuge test results. For this reason, it was decided that the draft paper should be revised and published for the benefit of the wider industry.

This paper provides a comprehensive case history of the site, publishing further heave data to June 1989, giving a total of 21 years of heave monitoring. Further site investigation data and calculations are included for comparison. The data show that the presence of a basement did not significantly reduce the shear strength of the clay beneath it. The coefficient of consolidation of the clay was 38 – 52 m^2/year and long-term heave was still ongoing 21 years after the end of excavation.

Introduction

A basement was constructed at 124 Horseferry Road, London SW1 in 1966-68, originally as part of a new sorting office for the Post Office. The average depth from ground level to the bottom of the base slab was 11 m. Due to planning difficulties, construction work stopped after completion of the basement to ground floor level in May 1968, and the associated superstructure was never built. The site was left largely vacant until redevelopment of the site started in 1989. Following the insolvency of the first developer, the Channel 4 Television Company completed the scheme to provide a building for their new headquarters.

The heave movements of this empty basement were monitored between 1968 and 1989. May (1975) presented monitoring results from March 1968 to February 1973 and made predictions of future heave. Further excerpts of monitoring data up to 1989 were included in several publications about the design and monitoring of deep basements in London Clay such as Pumphrey (2001) and Chan & Madabhushi (2017), but the original monitoring data remains hitherto unpublished. The primary aim of this paper is to make public the full set of monitoring data for the benefit of the wider industry.

Site history

Table 1 lists significant events in the history of this site.

Date	Event
1746	Maps show that the site was covered by orchards.
1851	Wesleyan Training College (later known as Methodist Training College) was founded on the site.
1862-1938	Maps and aerial photographs produced in this period show very little change to the site during this period. Prominent buildings included a large masonry church, and several four and five storey residential and office buildings arranged in quadrangles with a seven-storey tower on the centre block.
1944	The site suffered from extensive bomb damage.
c. 1959	Start of demolition of Methodist Training College to make way for Post Office basement
1962	Site investigation carried out across the site
June 1966	Start of construction of Post Office basement
Sept 1967	Start of settlement and heave monitoring
Nov 1967	Completion of excavation
May 1968	Construction is stopped after completion of basement to ground level
1984	Aerial photographs show the site being used as a surface level car park
1988	Declan Kelly proposes to redevelop the site into a residential complex
Feb 1989	Site investigation carried out across the site
May 1989	Demolition of ground and lower ground floors of basement
June 1989	Final survey of heave before reconstruction of basement
1990	Declan Kelly becomes insolvent; Channel 4 Television Company takes over the development
July 1994	Completion and opening of Channel 4 development, which includes 100 apartments and a new Channel 4 headquarters.

Table 1: Significant events in the history of the site at 124 Horseferry Road, London SW1

The structure

The site is approximately 70 m x 90 m in plan (see Figure 1) and the ground level is at +5 mOD. The original design of the structure was for a 20-storey high steel framed-tower with a four-storey high surrounding podium and a two-level basement with vehicular access. The construction was terminated at ground level due to planning difficulties.

There were two levels of *insitu* concrete basement over a concrete raft. The top of the raft was at -5.9 mOD (10.9 m below ground level) and the raft was generally 1.2 m thick, thickened to 1.8 m in the centre (beneath the proposed tower block) and reduced to 0.9 m around the perimeter (see Figure 2 and Figure 7). The raft was constructed from the centre outwards, and provided support for internal raking temporary props to the diaphragm wall during excavation, which was initially supported by an earth berm and later by the raking props. The excavation was taken to a depth of 12m approximately. Permanent strutting was then provided at two levels by the upper basement and ground floor slab at -1.1 mOD and +4.34 mOD respectively. The walls were 0.6 m thick diaphragm walls cast in 1.5m widths extending into the London Clay by a minimum of 1.5 m (3 to 12 m below the underside of the basement). The diaphragm wall was incorporated as the finished basement wall. The structural details are shown in Figure 3.

The vertical effective stress at formation level before the construction of the basement was estimated to be 190 kPa. The net unloading due to excavation was 184 kPa, comprising 234 kPa of unloading due to excavation and 50 kPa of reloading by the new structure. The basement raft was only pinned down at the edges alongside the diaphragm wall so the centre of the basement was relatively free to heave. All sections of the diaphragm wall extended into the clay.

Site Investigation

Two site investigations were carried out, the first in 1962 before construction of the basement and the second one in 1989, about 21 years after completion of the basement structure. The locations of boreholes referred to in the text are shown in Figure 1. Figure 2 shows the stratigraphy superimposed on an east-west section through the basement. Although the excavation had slabs at three levels (May, 1975), in Figure 2 only the basement slab is shown for clarity.

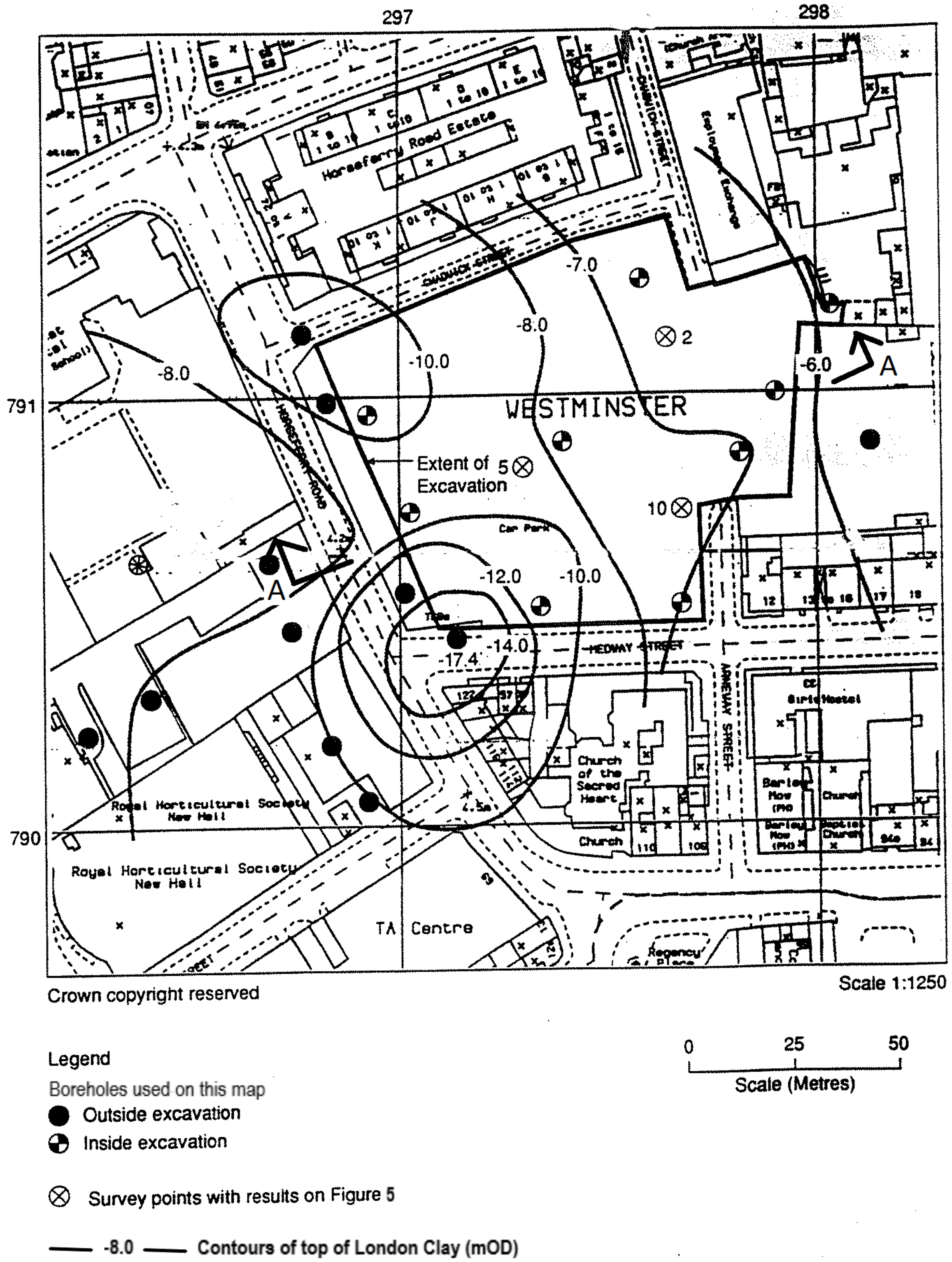

Figure 1: Site plan with locations of boreholes, survey points, and approximate depth contours of top of London Clay

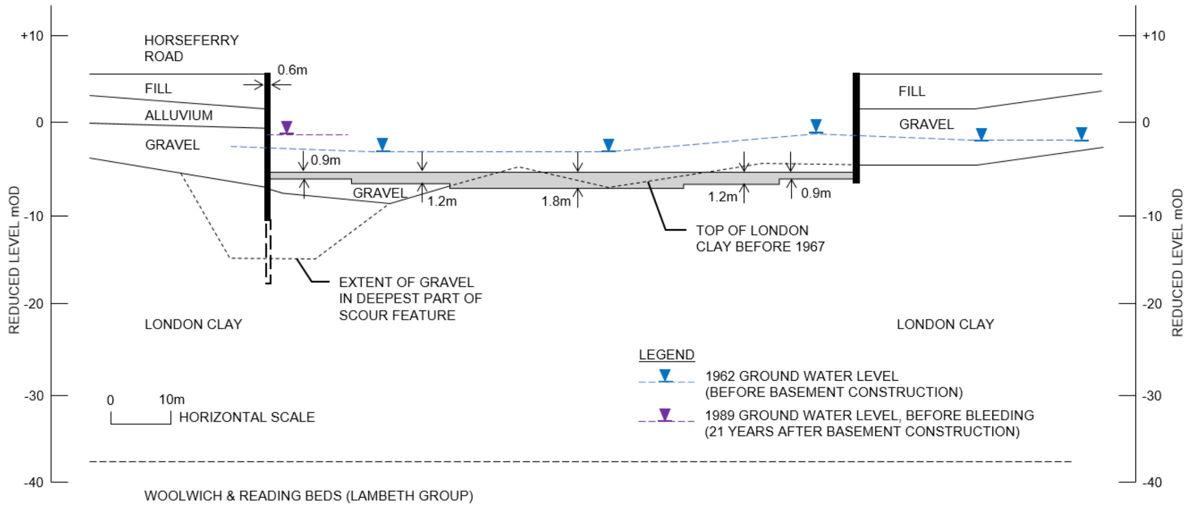

Figure 2: Indicative cross-section A-A (see Figure 1 for location) through basement, scale as shown

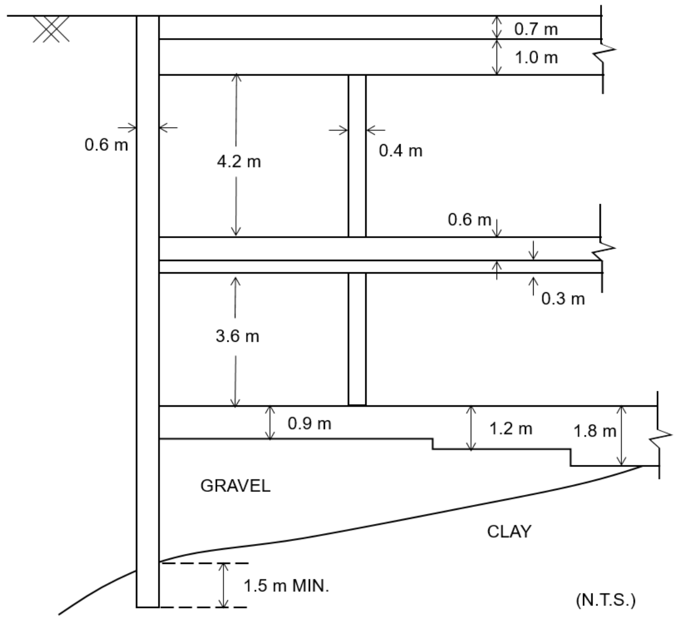

Figure 3: Structural details, following May (1975), not to scale

The geological map of the area (Geological Survey of England and Wales, Sheets TQ 27 SE, TQ 27 NE, 1973) shows a scour hollow to lie partially beneath the site. The origin and frequency of the scour hollows in London are discussed by Berry (1979). Contour of the surface of the London Clay as revealed by the site investigation are shown in Figure 1 and show the hollow to be about 10 m deep. The standard penetration test (SPT) shows that the Flood Plain Gravel towards the base of the hollow are loose to medium dense.

Groundwater levels during the 1962 site investigation (pre-construction) and 1989 site investigation (21 years after construction) are indicated on Figure 2. The 1989 groundwater level in the Flood Plain Gravel outside the site was found to be at about -2 mOD, some 4 m above the lowest floor level of the basement and similar to May's prediction of -2.5 mOD. Inside the basement, a bleed test performed during the 1989 site investigation showed that the ground water level before bleeding was at -2.5 mOD, similar to the external ground water level. The recovery of the water pressure after bleeding was very slow. These results show that the diaphragm wall was a reasonably effective cut-off to seepage flow, though sufficient time had passed since the basement's construction for ground water equilibrium to re-establish under the slab. It should be pointed out that this paper did not consider the global changes in water table in London.

The piezometric profile in 1989 (Figure 4) shows a near-hydrostatic distribution through most of the London Clay, followed by a sharp drop in head through the top of the Lambeth Group. The drop shows drainage into the lower aquifer and suggests that the Lambeth Group clay may have a lower vertical permeability than the London Clay locally. This finding is concordant with piezometric observations from nearby sites by Simpson et al (1989) and Nicholson & Harris (1994).

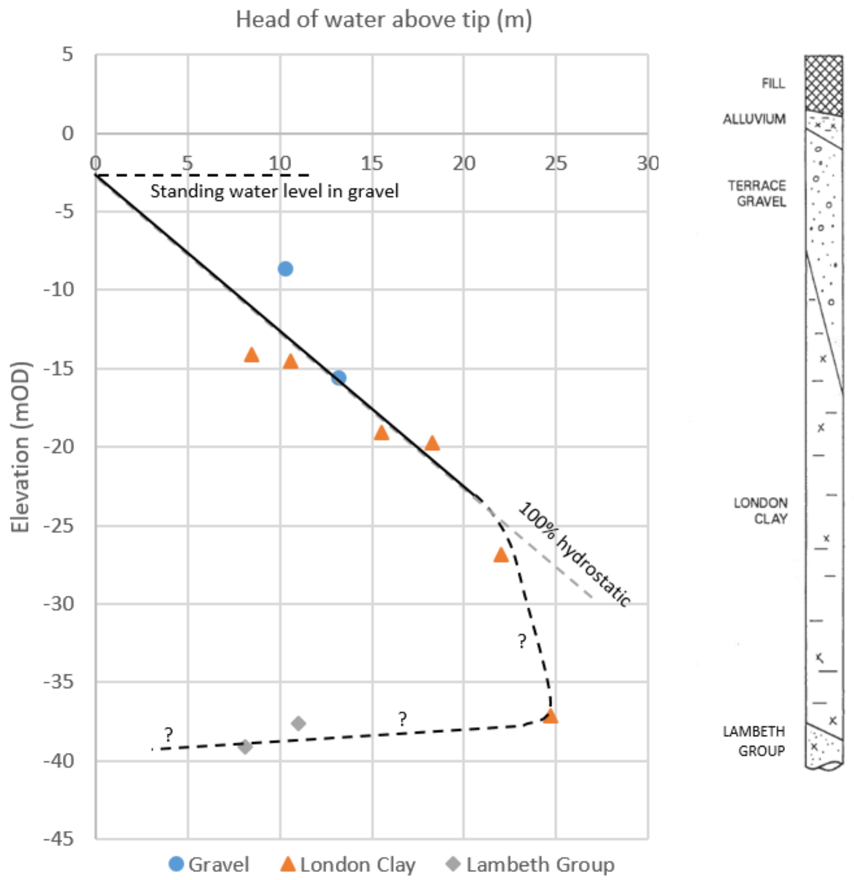

Figure 4: Piezometric profile from 1989 site investigation

Figure 5 plots the undrained shear strength results from boreholes both outside the basement and inside the basement alongside results from a site investigation in 1962. The 1962 strength data appears to be from undisturbed sample testing while the 1989 strength data is based on unconsolidated undrained triaxial tests on 102 mm-diameter samples. The 1989 site investigation also included SPT borings; this is reproduced in the Supplementary Data for completeness. The results outside the basement were from 1962 and 1989 while those inside the basement were only from 1989, some 21 years after the excavation of the basement.

A two-sample heteroscedastic t-test (Welch, 1947) was performed on undrained shear strength results at depths between -8 mOD and -18 mOD, to see whether the samples under the basement in 1989 were significantly weaker than the samples from 1962. This method involves calculating the mean and standard deviation of each set of strength measurements, then using the t-distribution to establish if the means of the two sets of data are different from each other in a statistically significant way. The results showed that the difference in strength profile between samples under the excavation and samples from 1962 was not statistically significant (Table 2). A similar analysis using the SPT values also showed that the results are not statistically significant. Nevertheless, it is noted that the recommendation by Padfield & Mair (1984) of 20% reduction in undrained shear strengths beneath an excavation is within the 95% confidence interval of the 1962 strength profile, which means the scatter of data at this site was too broad to confirm or disprove the 20% recommendation with statistical confidence. The dataset and calculations in this statistical analysis are available in the Supplementary Data.

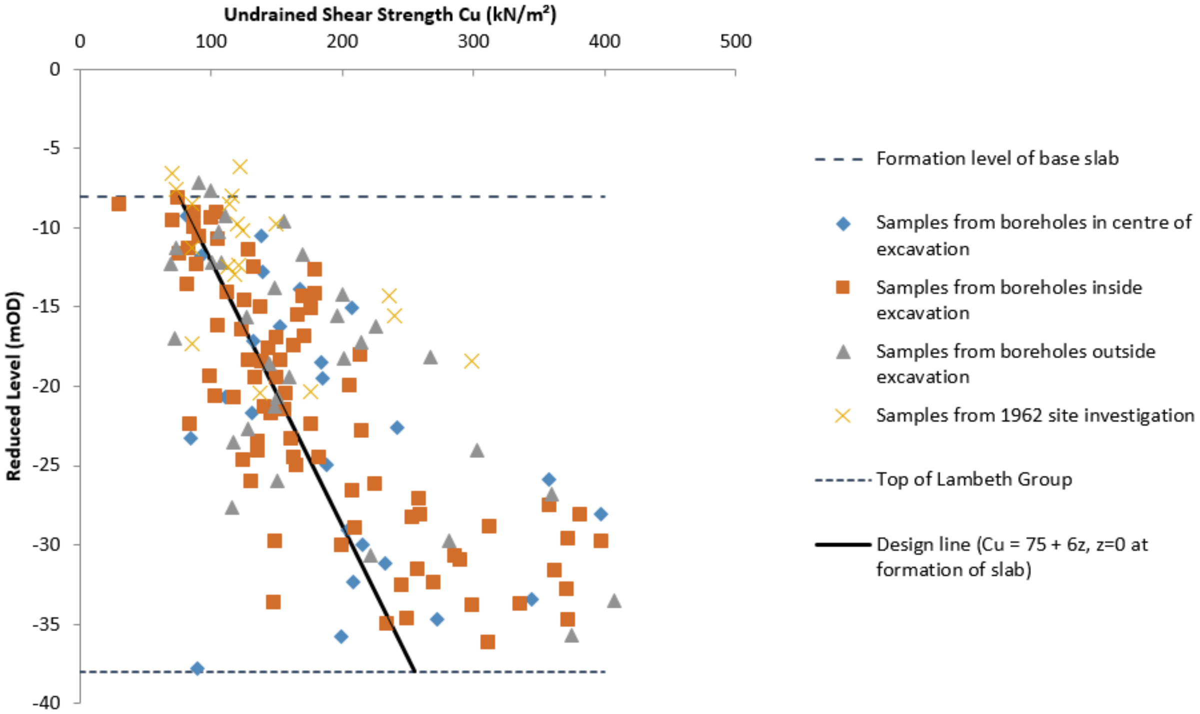

Figure 5: Undrained shear strength in London Clay

	Samples from 1962	Samples from 1989
Location	-8 to -18 mOD	-8 to -18 mOD, under basement
Number of samples	13	37
Mean (kPa)	131.3	123.3
Standard deviation (kPa)	50.5	39.9
p-value (t-test, 1-tail)	0.31 (not significant)	

Table 2: Summary of statistical test on strength data

Observations of heave

Twelve survey stations were installed into the basement structure at the time when it was constructed. A temporary benchmark was established at the lift shaft in the form of a steel bolt screwed to the inner wall of the central lift shaft, which in turn was surveyed from a benchmark located beneath a stopcock cover on Monck Street, 50 m east of the boundary of the site. The eleven other survey stations were in the form of rounded brass studs located within the bases of selected columns and concealed beneath steel covers. Figure 7 shows the locations of the survey stations.

Monitoring of settlement and heave began in September 1967. Measurements were taken multiple times a year until 1977, and then in May 1978 and November 1980. Arup undertook two more surveys in February 1989 and June 1989. The full set of monitoring data from 1967 to 1989 can be found in the Supplementary Data. Inevitably, some heave would have occurred between the start of excavation in June 1966 and the start of monitoring. The monitoring data showed negligible vertical movement between September 1967 and March 1968. May (1975) gave the following possible explanations for this:

1. As substructure construction progressed, the settlement due to the increase of structural weight offset the heave due to earlier excavation.
2. There might have been an error in the September 1967 datum measurement.

Noting that construction ceased around the time of the March 1968 survey, the remainder of this paper will take March 1968 as the datum of further analysis.

Figure 6 shows the development of heave with time from 1968 to 1989, when monitoring ceased. The locations of the survey points referred to on these figures are given on Figure 1. Figure 7 shows that as of 1989, the heave at the centre of the base slab was about 105 mm, whereas the edges of the slab heaved less than 70 mm over 21 years. This difference reflects the effects of the diaphragm wall around the perimeter of the basement.

The solid lines on Figure 6 show that the development of heave with time was generally consistent with one-dimensional consolidation theory. By 1989, the evolution of heave had reached the exponential decay phase but heave was still noticeable. It is estimated that long-term heave at the centre of the slab would reach 110 mm if the Channel 4 building was never built.

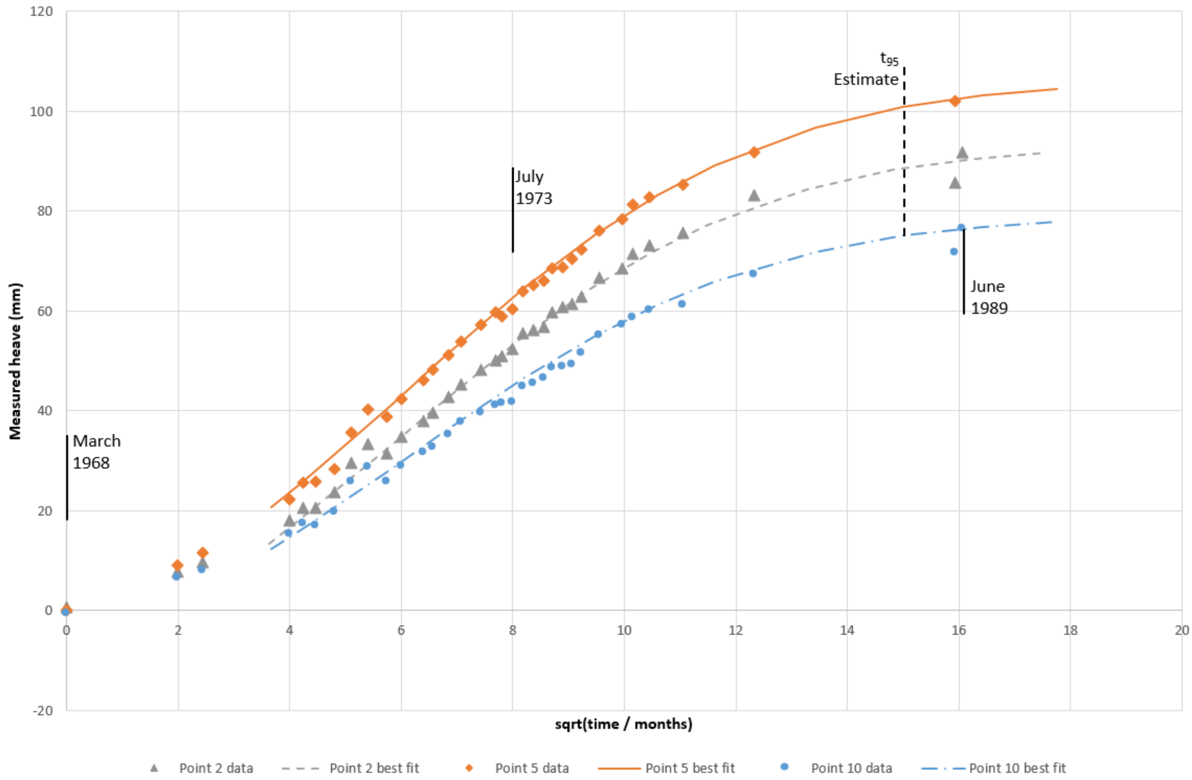

Figure 6: Development of heave with square-root of time

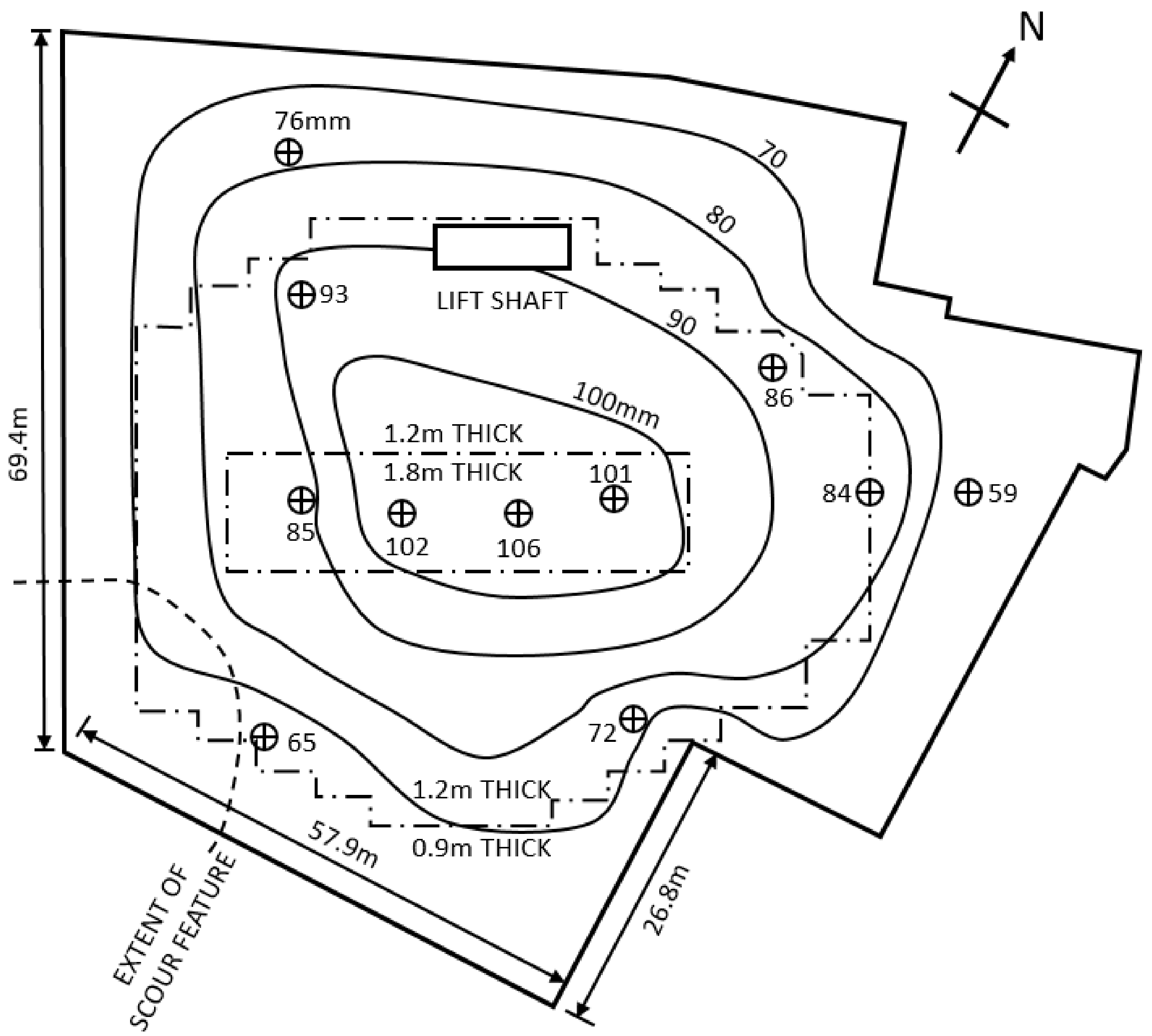

Figure 7: Measurements of heave on the base slab as of 1989, relative to 1968 datum, with approximate contours of heave. Dash-dot lines denote steps in slab thickness. Heave measurements in mm; slab thickness in m; plan dimensions in m. Scale as shown.

Analysis of heave

The overall thickness of the London Clay beneath the site is generally 32 m, reducing to 21 m beneath the centre of the scour hollow in the south-west corner of the site. The base of the London Clay layer was estimated as -38 mOD, underlain by the Woolwich & Reading Beds (now part of the Lambeth Group). The net heave per net change in total stress is estimated as 110 mm / 184 kPa = 0.6 mm/kPa.

Engineers of the Channel 4 project analysed the heave data using the one-dimensional settlement program VDISP from OASYS to provide reference values for the ratio between drained stiffness and undrained shear strength (E′/Cu). The analysis approximated the basement as a rectangular box with plan area 88.8m × 64.2m, underlain by 30.8m of London Clay followed by 16.5m of Woolwich & Reading Beds, the bottom of which was taken as a rigid boundary. Iterating between different linear distributions of drained London Clay stiffness, the analysis concluded that a strength profile of $c_u = 75 + 6z$ (kN/m²) (see Figure 5), where z is depth below the surface of the London Clay (-6mOD), and E'/Cu = 350 provided the best fit. Further details of this analysis are available in the Supplementary Data.

The time constant $t_{ref} = \frac{d^2}{C_v}$ is extracted from the best-fit consolidation curves of each of the 11 monitoring points (Figure 6 show the best-fit curves of three monitoring points; calculations for all monitoring points can be found in the Supplementary Data). *d* is the drainage distance and c_v is the coefficient of consolidation. t_{ref} is the time (in years) at which the dimensionless time Tv = 1 in one-dimensional consolidation theory, corresponding to approximately 95% consolidation in terms of linear displacement. The values of t_{ref} range from 17 years to 21 years, with the lower values coming from locations where the top of the London Clay was the deepest according to Figure 1. This is to be expected because a depressed clay-gravel boundary implies a thinner clay layer and thus shorter drainage distances.

Using these values for t_{ref}, it is estimated that consolidation was 96% – 98% complete as of 1989. Taking the values of t_{ref} and the estimated thickness of the London Clay layer beneath each monitoring point (27 – 31 m), a single-drainage consolidation calculation gives the range of the coefficient of consolidation c_v as 38 to 52 m²/year. The bottom of the London Clay is considered to be an impermeable boundary following the aforementioned discussion of ground water conditions which suggests the Lambeth Group clay was likely to have a lower vertical permeability than the London Clay locally. It should be noted that May (1975) considered the base of the London Clay as a drainage boundary, which would lead to a double drainage calculation giving c_v = 10 to 13 m²/year. These interpretations ignore the effect of horizontal drainage along silty layers in the London Clay. The values of c_v from this site are significantly higher than the typical values ($c_v \approx 3$ m²/year) for London Clay derived from field measurements of permeability or element testing of undisturbed block samples, which may be because the rate of consolidation in stiff clay is driven by preferential drainage along fissures (Nicholson & Harris, 1994; Ng, 1998).

Conclusions

1. The evolution of heave displacement with time agrees with predictions by one-dimensional consolidation theory.
2. A comparison of shear strength data from two site investigations 27 years apart did not show a statistically significant loss of shear strength due to heave of London Clay caused by the presence of the basement.
3. The ratio of drained stiffness to undrained shear strength (E'/Cu) was estimated as 350 for this site.
4. The coefficient of consolidation (c_v) was found to range from 38 to 52 m²/year, assuming an impermeable boundary at the base of the London Clay. This value is much greater than the typical value of c_v = 3 m²/year from laboratory tests and field measurements of permeability.
5. Long-term heave was still occurring 21 years after the end of excavation.
6. The net heave per net change in total stress was estimated to be 0.6 mm/kPa.

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Supplementary data

Further details on the heave monitoring data, the site investigation data, and the calculations presented in this paper are available via the Cambridge University Data Repository at https://doi.org/10.17863/CAM.27523 .