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The diagnosis and arresting of settlement within Westminster Hall in the Houses of Parliament, London

J.D. Miller
MA CEng MICE MIStructE Membre CNISF, Technical Director, Gifford

ABSTRACT: This paper considers the necessary pre-requisites for a successful conservation project in terms of the profile of the consultancy team, its relationship to the client and curatorial representatives and the functioning of the contract for execution of the works. It also draws out a number of examples of interest from the project at Westminster Hall:

- Issues of document research and archiving
- The nature of the initial comprehensive diagnostic investigations
- The safe application of heavy ground engineering techniques in the context of materials of very high archaeological significance
- The conservation philosophies applied to the work
- The conclusions of the post-project review.

1 INTRODUCTION

Westminster Hall is an extraordinary building. It has witnessed social change as English monarchical power has evolved into British parliamentary democracy. It has been the seat of the Exchequer, the home of the highest courts and some of greatest trials in the land, it survived a devastating fire of 1834 that destroyed The Palace of Westminster and it became a classic example of modern roof restoration in the 1920's. Its very size and location defies the designers of the present to achieve in materials and engineering what the masters of building achieved 900 years ago. Now, locked within the security cordon of the Houses of Parliament, it remains perhaps one of the country's best-kept heritage secrets, on view only to those who queue to tour the Palace of Westminster.

The desire to improve the visitor's experience and security arrangements at the Palace of Westminster lead to the development of a new Visitor Reception Building and this afforded the opportunity to address a long term problem of settlement within Westminster Hall.

The Hall was built for William Rufus, son of William the Conqueror, in 1097–1099. He chose to site the building close to where the ancient River Tyburn joined the Thames in the former inter-tidal zone. The walls of the Hall themselves are founded on Terrace gravels at some 4 m depth. The Hall that he erected was immense by medieval standards, measuring 20.7 m × 73.2 m; it was a sign of power at home and abroad. Three hundred years later Richard II increased the height of the walls and re-roofed the building with thirteen huge hammer beam trusses, built by Hugh Herland. He also reworked the interior, making his own mark in carvings in oak and stone with images that convey a divine connection with royal power.

Westminster Hall was the seat of royal power. Coronations of monarchs from were held here, and the Kings presided over courts and hosted lavish banquets. Later, highly respected architects including William Kent and Sir John Soane added structures in and around the Hall and as the function of the Hall changed these were subsequently removed (Figure 1).

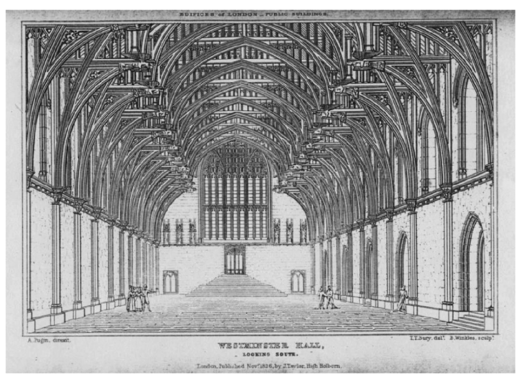

Figure 1. Westminster Hall looking South before Barry's transformation.

Of particular interest to us is the history of the floor of the Hall. It appears that the original medieval masons took steps to address the poor ground they found when they laid the earth floor by capping the ground with a layer of compacted clay. Richard II laid a Purbeck stone floor.

Then between 1834–7 Robert Smirke, architect for the British Museum date and Somerset House, undertook extensive excavations and archaeological recording of the ground and earlier floor levels as part of his restoration of the Hall and the building of the floor we see largely unchanged today. He built it using some 500 Crosland Hill York flagstones each weighing around 750 kg, supported, as we confirmed during this project, on approximately two-courses of brick sleeper walls around the edges of each flag. These walls were supported on a 400 mm thick mass lime concrete slab.

Sir Charles Barry, with input from Pugin, won an architectural competition for designs to rebuild the Houses of Parliament. His vision was for Westminster Hall to become the entrance to the Houses of Parliament. In 1852 he transformed the Hall by removing the arched window from the south wall of the Hall to create an opening to the new St Stephens porch. He added a magnificent processional accent steps from Westminster Hall to St Stephens Porch thus creating a staged setting and continuous movement of people in the previous static layout of the Hall. He constructed the steps by supporting Hopton Wood stone treads on a series of closely spaced brick walls and piers with arched openings to allow access across the under the stair space.

Westminster Hall is Grade I listed and part of the UNESCO Westminster World Heritage Site.

2 BRIEF

The substantial structural movement apparent in Smirke's floor and Barry's staircase are the subject of this paper.

However, this project was undertaken in parallel with a separate project to build a new Visitors' Reception Building. Visitors were to, in future, enter the Palace of Westminster through the North doors of Westminster Hall, walk through the Hall, up the imposing South Steps and into St Stephen's porch and the Houses of Parliament, a route that recognizes Barry's vision. Therefore, the condition of the Hall became more pressing to the Parliamentary Works Services Directorate and there was a rare opportunity to close the Hall to the public and carry out repair works. Upon visiting Westminster Hall, approximately 180 mm settlement was immediately evident in the lower flight of the South steps and in the floor close to the steps.

The brief for this work was to diagnose the cause of the settlement to the floor and steps, consider options for repair and recommend treatment for the problem. An OJEU notice was published by the Parliamentary Works Services Directorate towards the end of 2004 and Gifford were appointed to carry out the commission, commencing in January 2005. The brief invited best conservation practice because it required diagnosis of the cause and options to be presented, not just a solution. The brief also included new railings to the steps and a new plant space beneath the steps but these aspects are not discussed in this paper.

3 RESEARCH

From the outset, considerable time was spent by the project engineer and archaeologist in the early stages of the project researching the archives with the Palace Archivist, and the Institution of Civil Engineers, amongst other records. These provided initial background knowledge of the site and history of Westminster Hall and then, as the project progressed, the archaeological team was able to search for specific information to inform, interpret and explain findings from the site work. So the project gradually added to the body of information about the site. Archaeological research examined the site from times when inter-tidal sediments were deposited, research continued through the history of the construction methods and materials to the social and political use of the Hall, all of which were pertinent when piecing together the value and significance of the Hall and interpreting geotechnical data.

Research also yielded invaluable details of settlement monitoring work from the 1940's, drawings showing some construction details of the nineteenth century steps and proposed repairs in the 1960's. As consultants we were in the rare position of having movement monitoring of sorts for a period of some 60 years, about half the life of the present steps. Amongst other information, the early research gave four sets of data on floor settlement over a total period of around 60 years. It was clear from this that the movement of the steps showed no signs of stopping, with an additional 16 mm of settlement in the centre of the floor being recorded between 1992 and 2004 (Figure 2).

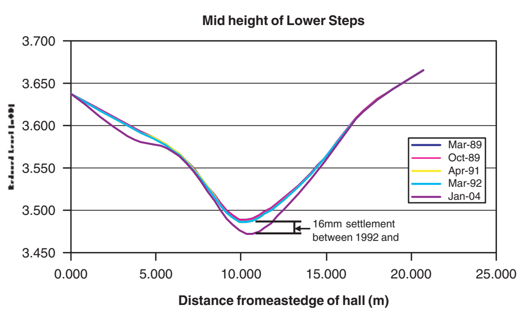

Figure 2. Deflected profile of the steps from East to West.

This historical monitoring was assessed and suggested historical and ongoing settlement of approximately 1 mm a year.

4 INVESTIGATIONS

However, although one or two boreholes were available for areas close by, very little engineering data or calibrated properties on the ground conditions was uncovered by research for the locations beneath the steps and floor. It was clear that to both correctly diagnose the movement and to support any discussions with the curatorial bodies with regard to intervention, a major ground investigation needed to be carried out, and that the success of this would be key to the quality of decisions made thereafter.

It was also important to gain as much as information as we could through non destructive testing, so a two stage approach was developed; firstly commissioning a suite of geophysical tests to determine the floor construction and as much about the ground below as we could, across the whole of Westminster Hall and secondly targeted lifting of flags to confirm the construction and intrusive geotechnical boreholes.

A suite of non destructive tests comprising geophysical radar, microgravity and resistivity was commissioned. Whilst the specification and execution of such non-intrusive investigations was an essential part of the initial work in the context of the Hall, at the time they were interpreted they were of marginal value in defining sub-floor and deeper features of stratigraphy. With developments in processing of geophysical testing there may still be more information to be gleaned from these results.

Faced with the value of the historic fabric within the Hall it quickly became apparent that any work, including investigations, would require significant intrusion into the building. Thus the design of such investigations would require considerable thought. To make an appropriate diagnosis of the causes of settlement and to design an appropriate solution we needed t a robust theorem as to the cause of settlement, as there was much speculation based on fragments of evidence. It was essential to have a comprehensive reliable geotechnical data for diagnosis.

Fundamental to this was the assumption that data could actually be obtained. Any investigation would require the successful lifting and relaying of floor flags within the Hall, something that no-one working on the staff in the Palace had witnessed before. The 1.6 m square flags have tight or minimal joints and there were concerns that lifting individual slabs might not be achieved without major dismantling from the edges of the Hall, or that flags might be dropped, cracked or not be re-laid satisfactorily Equipment was therefore assembled for a trial lift one weekend in the presence of the Conservation Architect. The joints between the flags were carefully cut free using hand tools and where necessary, after careful reflection a small disc cutter. It was found important to completely free the joints otherwise spalling started to occur at the edge of the flag. A single stone flag was successfully freed and relaid in the middle of the area of settlement, revealing Smirke's construction of dwarf sleeper walls and oversite concrete slab below (Figure 3).

Once it had been established that the flags could safely be lifted, ten flag stones were selected at locations across the Hall, concentrating on transects across the areas of settlement but with one chosen at the North end, remote from the steps. At each flag location two cores were taken through the 400 mm concrete oversite slab to enable Dynamic Probe Penetrometer testing and allow the retrieval of MOSTAP thin-walled samples for visual analysis and archaeological recording. The Penetrometer was mounted on a portable rig specially made for the project and surcharged with 4 tonnes of dismountable kentledge, which permitted penetrometer readings to be taken down to a depth of around 7 m, at which point the kentledge lifted on the underlying material, presumed to be stiff clays and gravels. Ground water level was monitored and found to vary by just 55 mm compared with tidal variation or between 4 and 6 m. Samples of the stone flags were taken for petrographical analysis to identify the quarry from which the flags had been won. Interestingly the

Figure 3. Trial lifting of the stone flags.

Figure 4. Dynamic Probe and MOSTAP sampling rig.

stone masons' visual identification of the stone source was confirmed by the laboratory testing, so it is always worth asking Samples of the concrete oversite slab were also taken and tested for strength and composition. Work was carried out at weekends through late May and June 2005 whilst the Houses were not sitting, at a rate of one or two locations per day (Figure 4).

Under the steps it was observed that in places the brick support had settled and so the steps were in effect hanging. Beneath the lower flights of the steps headroom was very restricted and it was not possible to undertake the dynamic probing and thin walled sampling. Instead we examined some pre-existing excavations in the concrete slab. These revealed information about the steps foundations and some stone fragments of archaeological interest. We also carried out PANDA tests, which in essence con sisted of a man striking a probe into the ground and measuring physical resistance.

Archaeological attendance on the investigations yielded some exciting finds in both building recording and examination of the recovered cores. The lifting of slabs showed evidence of the trackway support of the mobile access scaffolding used by Sir Frank Baines in the repairs of the roof in the 1920's, with a fragment of newspaper dating from 1922 being found. The soil cores showed evidence of a rammed chalk floor in the Hall, the stratification giving some indication that this had been built up over centuries, possibly as previous settlement had taken place.

5 DIAGNOSIS OF SETTLEMENT

The quality of data obtained from this investigation was consistently high, allowing the classification of soils and the soil strength and stiffness to be measured directly in-situ with the probe and correlated through the testing shear strength of recovered soil samples using established conversions with design parameters being determined in-situ and correlated to shear strength using established conversions. The samples were examined by geotechnical engineers and archaeologists together, collaborating to enhance their understanding and produce a single interpretation of the ground: there is only one reality, not a 'geotechnical' interpretation and an 'archaeological' interpretation. The investigation revealed that overlying the London Clay formation is a layer of Terrace Gravels, then a succession of soft and loose alluvial deposits, then made ground that formed the dry land for Westminster Hall and then a sequence of earth floors.

The results showed that material at a depth of between roughly 1 m and 3 m below the floor at the base of the steps comprised very weak alluvial clays with some organic content and varying in thickness. It is this local area of weak clay alluvium that is gradually compressing, and causing settlement, the problem is exacerbated by the additional load due to a large stone candelabra support structure of considerable weight. Further to the North, this material became firmer, giving way to terrace silty sands and sandy gravels (Figure 5).

The diagnosis was, therefore, that the floor and steps were likely to be settling because of the weak and organic materials present locally below, with constant internal shearing of the soil resulting in continuous movement.

6 DESIGN APPROACH AND CONSTRAINTS

Thus it had been established that the basis of the problem was essentially a ground engineering issue with possibly very significant archaeological impact, and so strong representation was made by specialists within the company in both these disciplines.

Alongside the conservation structural engineer and project director these formed a tight group of four individuals who remained close to the project throughout. The project director also adopted the separate role of lead consultant. The internal team structure for the project was a key factor in delivering what we believe to be a highly successful project.

Once the cause of settlement was understood we held team workshops to brainstorm different options for remedial solutions. This approach meant that we were working as one multi-disciplinary team. Each discipline, structural engineer, archaeologist and geotechnical engineer had a good understanding of the problem, the brief and the site and an appreciation of the other disciplines, each was able to offer possible solutions and assess the advantages and disadvantage of schemes. This offered an integrated approach that was very different from three specialists each working to a limited brief or a solution produced by one discipline to be commented on by the others.

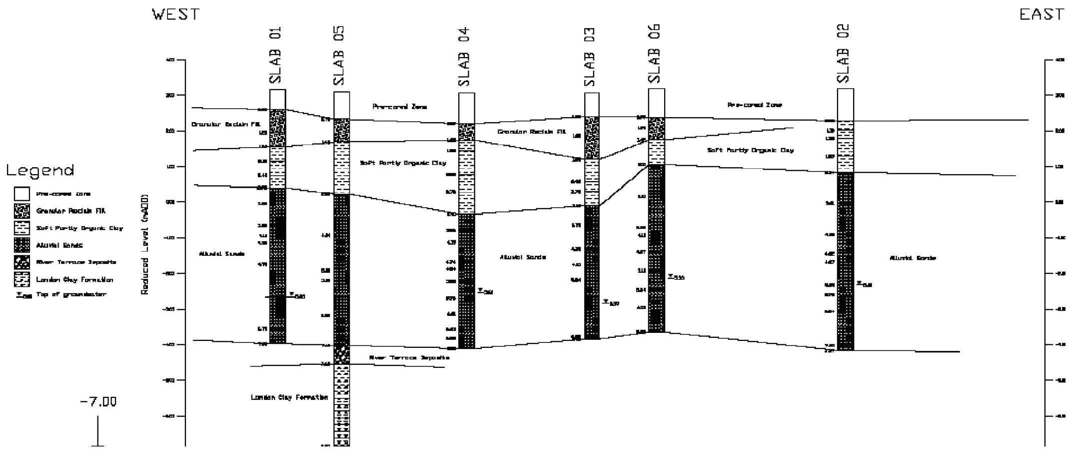

Figure 5. Geotechnical section showing layer of very weak alluvial clays.

The key issues and priorities of each aspect project discipline were captured, including operational requirements peculiar to the Houses of Parliament and noted project constraints against which we could assess the suitability of possible solutions.

7 OPTIONS AND DESIGN OF PERMANENT WORKS

The full Gifford project team met to consider the data and final options. Any option appraisal for conservation works should start with the option and implications of doing nothing; of leaving the building as found. Although the brief had indicated that works were anticipated, this was the assumed starting point for the scheme to develop the correct conservation approach. We also needed to assess the necessary extent of the repair works. We considered that it was not necessary to carry out major intervention to all flights of steps, just the lower flight, where settlement was worse, and we selected an area where settlement of the floor was greater than 20 mm, in both cases our intent was to minimise the interventions.

Different options were considered for the correction of the steps and for the floor, but these can be broadly categorized in to the following approaches each with their advantages and disadvantages:

1. *Do nothing and monitor further*.
   It was evident that the movement of steps and floor was continuing and not showing signs of abating and that further settlement would exacerbate uneven floor surfaces (a real concern given the future increase in footfall), and also result in an increasing risk of damage to the elements of the building fabric, such as the candelabra support structure and railings. 'Do nothing' can only be judged to be sound conservation practice if it does not make the situation worse. Although there would be no impact on the below ground archaeological remains, the movement would not be arrested and the brief would not be met.
2. *Dismantle and re-level the lower steps and floor without any foundation strengthening*, in effect correcting the superstructure or symptoms without addressing the substructure and cause. This approach has the advantage of appearing to solve the problem by lifting and packing stones to create a level finish with out interfering with the below ground archaeological potential. If the movement continues at between 1–1.5 mm a year, the flags could be lifted say every 70 years and an acceptable level finish maintained. Indeed, in 70 years time new technologies could make other approaches viable. However, it does not address the mechanism of settlement. In effect this is the approach that appears to have been taken throughout the life of the Hall to date; there is stratigraphic evidence of the earth floors being re-laid and documentary evidence that a number of stone floors have been re-laid, presumably because they were no longer satisfactory. In the past, however, there has not been the option to address the underlying cause of settlement and every time the flags are lifted and re-laid, there is a risk of damage.
3. *Dismantle and re-level the lower steps and floor, and strengthen the ground beneath the floor and steps to permanently arrest settlement.* Within this approach a number of different underpinning or ground strengthening options were considered. Under the steps these included mini piling or trench underpinning. Under the floor ground strengthening by compaction grouting or soil fracture grouting were considered. These solutions addressed the mechanism of movement but clearly had more impact on the archaeological remains, in

Figure 6. Rig for insertion of compaction grouting tubes.

line with the outlined constraints above, the mitigation strategy ensured that these impacts were limited, observable and measurable.

The chosen approach, presented in the final sketch plan submitted to the Client, was the third of these. The lower flight of steps and brick wall supports was dismantled down to over site slab level and mini piles installed with ground beams to create solid foundations to the steps. Under the floor initially it was proposed to strengthen the ground using dry soil mixing whereby a dry lime-cement mix is mixed into the weak layer of alluvial material to stiffen it. However, this presented practical problems and would have damaged the archaeological potential in this stratum. The final design strengthened the deep ground strata below the floor by carefully injecting columns of stiff grout under pressure in a controlled method to provide lateral compaction to the deep strata, known as compaction grouting (Figure 6). The archaeological remains, located principally in the top 1–3 m of material were not extensively damaged by injected grout as it was injected here at hydrostatic pressure, in effect creating piles passing through the layer. So the impact on the archaeological potential was limited and known. The depth and pressure of the grout columns were carefully controlled to reduce the increase in stiffness of the ground adjacent to the unstrengthened area of floor.

In addition, the oversite slab was strengthened. Under the steps, new reinforced ground beams above the piles were cast within the depth of the existing oversite slab, reinforced with stainless steel bars to give a design life of nominally 500 years (comparable with cathedrals) to support the brick crosswalls. The steps were rebuilt on new crosswalls. The oversite slab beneath the floor flags and dwarf walls was reinforced with a grid of stainless steel bars, in effect it was post reinforced to spread the load to the point supports at the grouting locations The area of strengthened floor was dowelled into the area of unstrengthened floor to ensure continuity across the floor.

8 IMPLEMENTATION AND DESIGN DEVELOPMENT

8.1 *Protection to the floor*

The Hall was closed to the public in January 2006 and site work commenced with the protection of the flags by covering with polythene throughout the Hall and then laying 75 mm thick close-boarded timber protection overlaid with plywood boards to form a trackway along the centre of the building from the North door off New Palace Yard. The weight of plant and the stacking of storage materials was restricted to avoid overloading the flags, which were only supported around their perimeter by dwarf walls.

8.2 *Lifting the flags*

Dismantling of stonework was assisted by a suction lifting device slung from of a 7 tonne capacity tele-handler. One of conditions of planning approval was the safe, protected storage of the stonework once removed from site. Flags were carefully labelled to an agreed method and taken to a bonded warehouse in East London, where they were held until reconstruction commenced.

8.3 *Archaeology*

Another planning condition, and an integral part of the solution was the implementation archaeological mitigation strategy. Two test pits were identified and discussed in detail with the Conservation Architect and English Heritage. One measured 2.5 m × 3.5 m by 2 m deep, and was located close to the suspected location of a medieval hearths for the great fires, lit to heat the Hall. The other was sited close to the Western candelabra pillar, at a location where fragments of medieval masonry had been found during earlier inspections of the sub-step void. These excavations were programmed to be excavated in advance of main groundwork operations, whilst dismantling was still

Figure 7. View towards South end of the Hall during archaeological mitigation work.

taking place elsewhere around the Hall, and so did not result in delay to the overall programme (Figure 7).

The pits were excavated as part of the main contract work, with the archaeological field work being undertaken as a named subcontractor. The first pit revealed detail on the progression of nearly a thousand years of rammed chalk floors, but no evidence was found of the hearths. However, the pit by the candelabra support revealed a succession of masonry fragments identified as parts of the King's Table that stood at the end of the Hall in medieval times. The find was of great significance and was widely reported in the national press and archaeological journals.

The excavation for ground beams supporting the lower landing of the steps exposed a small area of earlier flooring. This was recorded and the ground beam redesigned locally to step up and over the feature, which was covered with a layer of inert sand and so preserved in-situ.

8.4 *Concrete slab*

The concrete oversite slab was a very weak lime based concrete and the lack of binder meant that when the concrete was cored loose aggregate became jammed in the drill, slowing the progress of drilling. Once this became evident, an early review of the design of the strengthening of the slab was undertaken and as a consequence, instead of drilling and coring stainless steel bars and grouting them in place the method of strengthening the concrete was changed. Instead slots were chased in to the slab and bars laid into the slots and grouted in place.

The intention was to keep as much of the sleeper walls as possible, however sections needed to be cut out in order to insert the reinforcement bars. The walls were rebuilt in concrete for speed and ease but also to clearly differentiate the modern work.

8.5 *Relaying of the stonework*

Only the lower flight of step were dismantled and relevelled so the treads had to be relaid to match the deflected shape of the remaining steps and then relevelled across the landing to a horizontal edge at the top of the lower landing, This presented difficulties as the stones needed to be laid with falls in two directions. Consultation with the stone mason and the use of lines to gain approval of levels, ensured that this was successfully achieved. The lower flight was then kept level. When stones were cracked a number of repair methods including doweling stone inserts, repointing of cracks with lime and in places repairing cracks with epoxy resin, and piecing in carefully matched stones produced a good result.

Overall a partnership approach to solving design and implementation issues was adopted and this resulted in good progress on site and completion on time.

9 POST-PROJECT REVIEW

The project offered a rare privilege to work in one of the most important and stunningly beautiful historic buildings in the world. The work was completed on time, on budget, with no damage to the historic fabric, it looks fabulous and met with the approval of English Heritage and the Client. Like any successful project there are always a number of indefinable reasons why things worked but we can also learn a number of lessons that are transferable to similar projects:

1. A good *geotechnical investigation* is essential so that decisions can be based on facts.
2. Technical decisions were influenced by client requirements *and* good conservation principles. We did not always give way to client demands but maintained best practice which ultimately fulfilled the client's aspirations.
3. There is sometimes the need for *brave*, but not reckless, *decisions*. For example to lift a significant

number of flagstones to undertake geotechnical investigation.

4. A *good brief* is very helpful, in this case requiring cause, options and solution to be presented.
5. The design team worked as a *tripartite multi-disciplinary team*. Each discipline shared in the aspirations of the project goals and there was a strong desire to understand and to compromise but also to stand firm when required. There was mutual respect across the team and healthy argument.
6. During the design process there were a number of previews, reviews and combined site visits. *Communication* was face to face not through emails and minutes.
7. There was realistic *fee* for the work.
8. The *subcontractors* were very good and their ideas fed into design development. Ultimately, however tight the specification and supervision, the quality of the finished stonework is done to the master mason executing the works.

10 CONCLUSIONS

The design and construction team have repaired a very long term settlement problem in an historic environment using carefully chosen engineering technology and employing the least intrusive methods possible, but nevertheless methods that are of our time. The interventions were based on a very good understanding of the causes of damage. We have undertaken extensive recording of structures and have taken the opportunity to gain a greater understanding of Westminster Hall than existed before the project.

Client :
Parliamentary Works Services Directorate
Lead Consultant, Structural Conservation Engineer, Archaeological Consultant:
Gifford
Contractor:
Verry Construction Limited
Stonework Subcontractor: Stonewest Limited
Ground Engineering Subcontractor: Keller Foundations Limited
Archaeological Contractor: Museum of London Archaeological Service.