11TH INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

The practical structural assessment and design aspects of monitoring building structures with regards movements arising from tunnelling, using examples from Bond Street Station Upgrade.

Paul PERRY[1]

[1]Hewson consulting engineers, Guildford, Surrey, United Kingdom
Corresponding author: Paul Perry (ISFMG@in-conference.org.uk)

Abstract

The structural assessment and the design of the instrumentation array to monitor the movements is an important aspect for tunnelling projects. Whilst much has been presented, written up and taught, little is published on the practical aspects of designing an instrumentation array to suit the particular behaviour of a building structure.

The lack of mention in The Civil Engineering Procedure, allows ambiguity as to the expected effort undertaken at each stage of the development of a project.

Whilst the process of Building Damage Assessment is well established, the requirement to assess a significant number of buildings line-wide has grown in importance. Coupled with the need to provide large instrumentation arrays to cover numerous buildings, a risk may arise that a critical building is overlooked.

Even when the monitoring commences, the vast number of automated readings, if not studied carefully, may lead to a false sense of understanding of the building with a risk of missing action to mitigate.

Therefore, practical, timely and detailed research, assessment and review of such critical buildings is important to ensure such risks are minimised. Undertaking some of such detailed work earlier in a project brings benefits.

The paper considers when such detailed work should be undertaken, understanding building behaviour, and the practicalities of assessment and monitoring.

Using a number of case histories encountered on the Bond Street Station Upgrade, completed for Christmas 2017, key differences are described in a number of types of building structures.

Conclusions are drawn from this, suggesting best practice in terms of the structural engineer's interaction with regards the instrumentation and monitoring of building structures.

Keywords: Building Damage Assessment, Tunnelling, Instrumentation Monitoring

1. Introduction

Monitoring a building structure for movements set up by tunnelling to levels of damage criteria, on an urban civil engineering project, is not new. Instrumentation and Monitoring techniques have advanced considerably over the last decade and use of complex systems have been employed on Crossrail, the Upgrades and now HS2.

It assumes that the reader is familiar with the three stage assessment process (Mair et al, 1996) where buildings are considered and eliminated through a phased review, considering damage categories arising from predicted settlements and the adoption of protection measures where appropriate. Further refinement on this screening of buildings has been suggested (Devriendt et al, 2013) including the use of "virtual surveys" to assist in the sheer number of buildings to be assessed.

To be able to assess the likely behaviour of a building, deploy mitigation measures where appropriate and know what to monitor and when, is critical to effectively control tunnelling and ensure the safety of the building above.

The third stage of the process includes the need for a qualified structural engineer to review the individual building structure to form, an opinion of how the building is likely to perform, the existing stability provision, the likely sensitive areas and the need for specific, individual monitoring of certain building elements. Beyond the completion of the phase 3 assessment, further investigation, monitoring and subsequent structural assessment and design of any mitigation measures, is very dependent on what is found at this stage. Reference

should be made to the Institution of Structural Engineers Appraisal of Existing Structures, during this phased assessment.

Using Bond Street Station Upgrade and examples from some of the buildings assessed in this way, to allow tunnelling to progress below, will assist in illustrating this.

A number of conclusions are made at the end of the paper, including the earlier building research is undertaken, the better.

2. Civil Engineering Procedure

Civil Engineering Procedure (Kirkham, 2021 p3-4) describes the project lifecycle by a series of ten "generic" phases developed with reference to a number of project guidelines, including the Royal Institute of British Architects (RIBA), Plan of Work for building projects. The design of an instrumentation array and the detail for monitoring of an existing building in a tunnelling scheme is too detailed an aspect to be listed in these ten "generic" phases of Civil Engineering Procedure. However, in considering the feasibility to construction, it is proposed here that the effort deployed is as covered in Table 1.

Generic Phases of the Lifecycle of a Project	Building Damage Assessment	Instrumentation and Monitoring
Feasibility Study	Initial consideration of existing properties along the tunnel route is made and an Information Paper on Ground Settlement written to cover such issues as method of assessing settlement, monitoring, protective works, etc	Unlikely to be considered at this stage
Design	Design is progressed assuming that a phased assessment of ground movement is undertaken, with a more detailed approach during the construction phase, as is the norm for BDA, with a "Design and Build" contract.	Tender Drawings prepared by the design team may show a basic array of monitoring points at each building on the tunnel route, to accord with the phased assessment of ground movement described in Project Documents, such as the Information Paper
Procurement	Civil Engineering Contractor is sought, and following Tender actions, the contract is awarded. Provision made for BDA.	Provision made by the Tenderers based on the tender drawings
Construction	A phased assessment of ground movement is undertaken, with a Desktop Structural Appraisal being required in Phase 3 when the likely structural behaviour of the building is revealed, the effect from movements confirmed, mitigation and monitoring designs are commenced	The Tender drawn scheme is implemented to provide a steady state of results prior to commencement of the works. Supplementary instrumentation externally introduced at critical buildings Internal instrumentation is introduced to protect elements within listed buildings

Table 1: BDA and I&M response at generic phases of a project

Therefore, the effort employed at each generic phase of a project is not well defined with regards structural assessment of buildings and an emphasis should be to undertake more detailed work earlier on to assist in designing the instrument and monitor plan.

3. BDA practicalities

3.1 Desktop Structural Appraisal

With the design and construction of the Elizabeth line, Crossrail Information Paper D12 – Ground Settlement was issued to explain this three stage assessment process with regards the project arrangements for assessing, monitoring and mitigating the effects of ground settlement arising from the new railway's construction. This was also applied to the three London Underground "upgrades" at Victoria, Tottenham Court Road and Bond Street Stations.

Within this is included the need within the third phase for a Desktop Structural Appraisal, undertaken to confirm the likely behaviour of the building in question and a vital start to planning an effective instrumentation and monitoring plan.

It should be noted here that the Desktop Structural Appraisal ought to consider alterations made, especially those that would change the behaviour of the load bearing masonry or steel / concrete framed buildings and supporting foundations. Such alterations might not necessarily be obvious without reference to detailed as built drawings and undertaking a structural inspection of the existing building.

As the project progressed, and as required by the nature of the assessment of a building, the Desktop Structural Appraisal is replaced by a Report on the Existing Building and Alterations. This is regularly updated to include say any structural investigations to be undertaken, their rationale and an update on the current assumptions made of the building structure. This report can be kept for use by the project and not "caught up in" the process of discussing and agreement settlement deeds arising from the Building Damage Assessment process.

3.2 Assessing buildings

The structural assessment of a building, appropriately and effectively, is an important means to ensure the safety of the building, as well as the avoidance of unnecessary mitigation. This also sets up the parameters for monitoring the structure during the course of tunnelling and underground construction.

A couple of key practicalities, now surface.

Accurate information on an existing building is vital here, so obtaining archive records should be considered an important task, undertaken early in a project and constantly "topped up" during the progress through to construction. (For a detailed overview of this process see Perry and Thomas, 2009). This is a difficult subject to predict in terms of how long this takes and to the extent of information found.

Secondly, using this newly found archive information of the building structure, and undertaking effective analysis may then require to be supplemented by structural investigation, topographical survey and materials testing, a necessary part of detailed structural assessment. Allowing time for this in a programme can be a challenge.

3.3 Instrumentation & Monitoring

As detailed structural assessment of an existing building is progressed, it is only then that further specialised instrumentation and monitoring are identified. This will require installation and a period of "steady-state" for inclusion into the project programme.

4. Bond Street Station Upgrade

Bond Street Station Upgrade was included in the Crossrail Bill, in order to secure a scheme to relieve congestion at the existing station. A significant amount of tunnelling (approximately 70%) was included in the works that provide more escalators at depth and pedestrian tunnels allowing further points of access and egress at both Central and jubilee line platforms. It will also assist with interchange with the future Elizabeth line. Included in the works was a new northern ticket hall and entrance at Marylebone Lane, north of Oxford Street. Subsequently the Oversite Development was included in the contract, such that the frame could be constructed and used as a temporary tunnelling crane hall.

Figure 1 shows Stratford Place, north of Oxford Street and the arrangement around the new tunnels below and the settlement contours arising from the assessment of movements from the works.

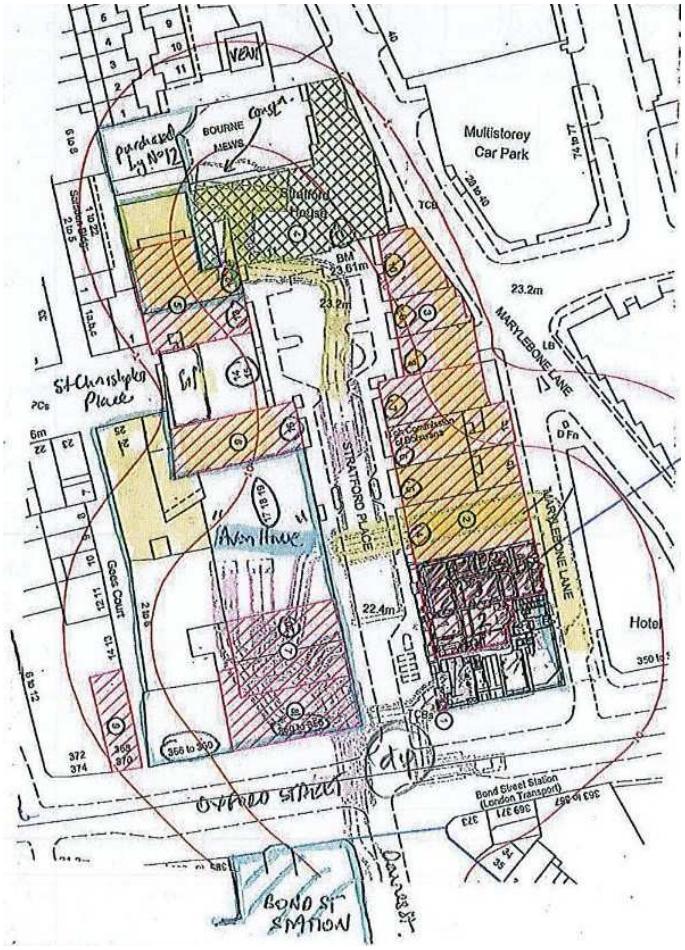

Figure 1: Building locations set around Stratford Place, north of Oxford Street.

The contract to construct the works was awarded by London Underground to Costain Laing O'Rourke Joint Venture in August 2010, with a design alliance of Halcrow Atkins appointed to progress the design through the detailed phase and on to construction and opening to passengers in December 2017. Existing buildings and their basements above needed careful consideration and with 57 buildings requiring consideration through the building damage assessment process, with some requiring detailed consideration. The scheme was recognised as one of the most complex tunnelling projects undertaken in the UK.

5. The Buildings effected

5.1 The Buildings above

The detailed design of Bond Street Station Upgrade was undertaken in, around and under Oxford Street involving tunnelling to extend the station, below a plethora of historic, diplomatic and complex altered buildings on a line of Georgian terrace.

Each Desktop Structural Appraisal had identified the building structure and likely behaviour, as best that could be done at the time of undertaking the ground modelling assessment. This was used ultimately in a reference point for the monitoring and where supplementary assessment had to be undertaken arising from the readings, taken, further assessment was undertaken. Compensation grouting was undertaken with a grout shaft installed at Stratford Place (see figure 2) with an array of tube-a-manchette (TAMS) drilled out to below the buildings requiring such mitigation, as was being used on the Elizabeth line (Lazarus and Jung, 2018).

Figure 2: Piling for grout shaft in front of No 2 Stratford Place.

5.2 No 2 Stratford Place

This building was purchased to allow creation of a new ticket hall on the north side of Oxford Street, with a new entrance onto Marylebone Lane, within a deepened basement. The ground floor formed the roof over the new ticket hall, with the floors above, retained for future use. This involved underpinning, jacking and re-support with the adjacent building fronting Oxford Street demolished to form to new combined commercial and station facilities with two shafts to depth to link with the new tunnels. Tunnelling at depth in front and the rear was advanced once a grout shaft had been excavated and brought into use. The BDA was progressed over several stages of works, with constant changing requirement for instrumentation and monitoring.

Building Damage Assessment particulars	Building Damage Assessment practicalities	Instrumentation and Monitoring challenges
Grade 2 listed, at the end of a Georgian Terrace, five storeys including basement and mansard accommodation, shared a party wall with Tanzanian Embassy Deepened basement for new ticket hall, a grout shaft construction (Figure 2) for ground treatment (Figure 3), then two shafts excavated adjacent from which tunnelling at front and rear were progressed.	Archive information, supplementary site investigation (trail pits & boreholes), topographical survey, structural investigation, chimney flue survey, strengthening of brickwork wall returns required. Accurate detailed load take-down needed to assist in creating the basement, jacking and re-support.	Supplementary monitoring introduced, such as tiltmeters to measure wall slope during the demolition phase for the end wall, located at the limit of the Georgian Terrace. Specific level monitoring of listed items, such as the staircase and ceilings at ground level and temporary works support.

Table 3: BDA and I&M practical aspects for No 2 Stratford Place

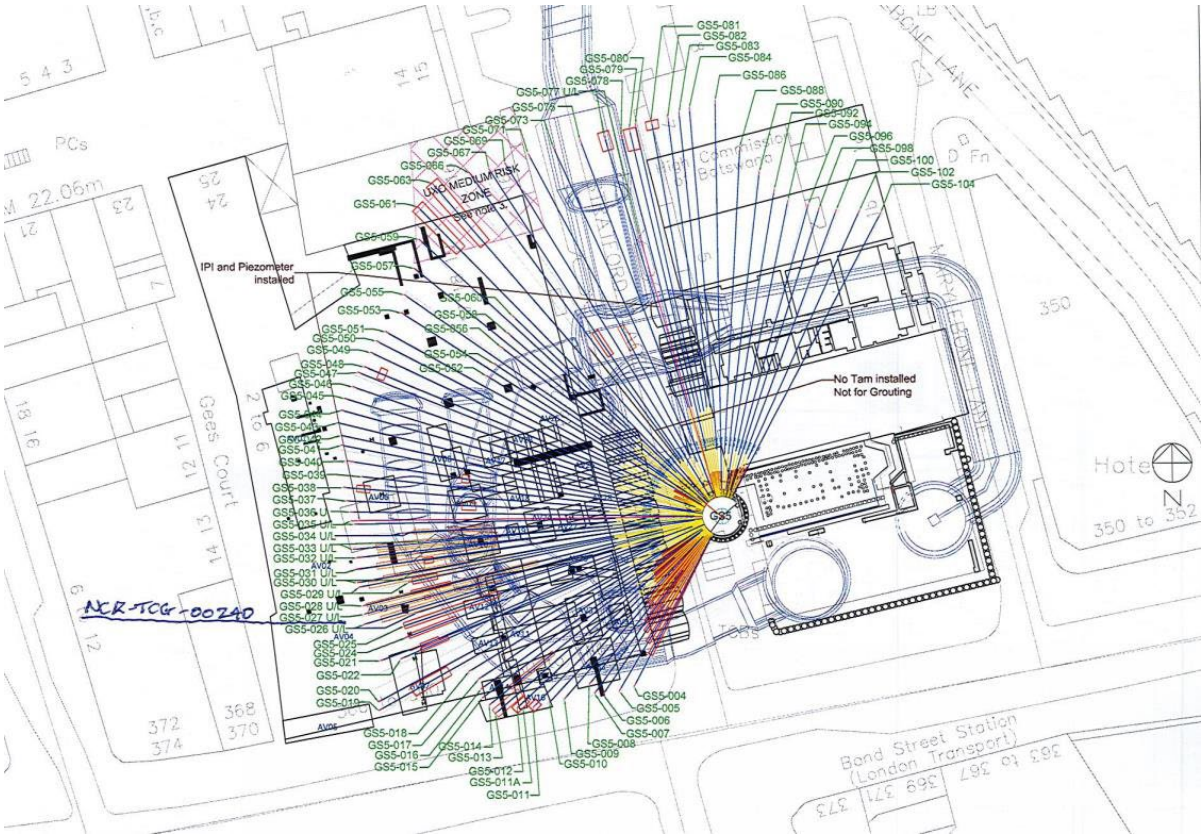

Figure 3: Grouting array below Stratford Place (reproduced by kind permission of Bachy Soletanche Ltd)

5.3 No 3 Stratford Place

This building is also on the eastern terrace to Stratford Place and was originally a Georgian private residence and now the Tanzanian Embassy following structural alteration to insert a frame and introduce pad foundations in lieu of the original strip footings. Tunnelling then occurred at the rear of the building and below the adjacent No 4 Stratford Place, necessitating grouting to mitigate settlements.

Building Damage Assessment particulars	Building Damage Assessment practicalities	Instrumentation and Monitoring challenges
Grade 2 listed, at the end of a Georgian Terrace, Five storeys including basement and mansard accommodation, shared a party wall with No 2 Stratford Place, to the south and the same with No 4 Stratford Place, to the north. Existing vaults below the pavement at the front and significant building extension at the rear. Diplomatic Use.	Building control archive drawings confirmed that significant alteration to open up the basement, replacing strip foundations with foundation bases with ground beams, to support columns with support beams in a storey height frame to support the ground floor and above. Accurate detailed load take-down needed for party wall loading, noting alterations in No 2 Stratford Place.	External monitoring points needed to be located to reflect grouting across the footprint, underground works to the south and tunnelling at the rear. Appropriate assessment of instrumentation reaching trigger levels when several elements of construction, grouting and tunnelling are being progressed concurrently, at one building location.

Table 3: BDA and I&M practical aspects for No 3 Stratford Place

The approach agreed between the project team and the embassy was akin to arrangements normally followed with a Party Wall Agreement. This proved beneficial to discussing and agreeing aspects arising from the Building Damage Assessment and the alterations required in the adjacent No 2 Stratford Place.

5.4 No 4 Stratford Place

The particular aspect here was the building was within the Georgian Terrace and had tunnelling coming from the rear, passing below the footprint of the building into the passenger concourse above the new escalators at depth in Stratford Place. A lift shaft within the building introduced earlier, needed to be investigated to ensure that the reduced cover to the crown of the proposed tunnel, did not force additional mitigation measures over and above grouting to ensure safe operation of the lift.

Building Damage Assessment particulars	Building Damage Assessment practicalities	Instrumentation and Monitoring challenges
Grade 2 listed, Four storeys including basement, shared a party wall with No 3 Stratford Place, to the south and the same with No 5 Stratford Place, to the north. Existing vaults below the pavement at the front and significantly extended at the rear with a further set of vaults below Marylebone Lane. Proposed tunnel immediately below and running along the length of the building	Building control archive drawings confirmed that alterations included floor strengthening, wall removal, stairs replacement and insertion of a lift to service the basement and upper floors. Subsequent supplementary survey, structural investigation & testing confirmed that the lift pit base was some 11m above the crown of the proposed tunnel.	Geotechnical instrumentation array and monitoring was in place and was reviewing once the tunnel construction sequence and methodology was confirmed. Arising from the Desktop Structural Appraisal, the nature of the connection between front façade and the internal walls was investigated, noting records had confirmed that enemy action during world war two had destroyed part of the façade. Instrumentation extent and Monitoring records were assessed

Table 4: BDA and I&M practical aspects for No 4 Stratford Place

5.5 No 6 Stratford Place

The existing building was another within the Georgian terrace and in use as the High Commission of Botswana. The building structure whilst similar to No 4 Stratford Place with a rear two storey annexe building, had major internal structural alteration following fire damage in the past. The new reinforced concrete staircase and lift shaft, with extensive wall removal complicated the assessment with regards to the stability provision.

Building Damage Assessment particulars	Building Damage Assessment practicalities	Instrumentation and Monitoring challenges
Grade 2 listed, Five storeys including basement, shared a party wall with No 5 Stratford Place, to the south and the same with No 7 Stratford Place, to the north. Existing vaults below Stratford Place, two storeys rear annexe, plus basement. Adjacent to the former Post Office Railway tunnel below. Diplomatic Use	Building control archive drawings confirmed conversion to offices from residential use, and then subsequent upgrading of the office accommodation Alterations included addition of the fourth floor, wall removal / re-support on steels spanning the building width, insertion of a new reinforced concrete stairs / lift shaft. Evidence of fire damage with subsequent repair.	Geotechnical instrumentation array and monitoring was in place at commencement of the works, however this needed review on receipt of the archive drawings with the proposed grouting and tunnel construction sequence to be adopted on site.

Table 5: BDA and I&M practical aspects for No 6 Stratford Place

5.6 The Oriental Club

The Grade 1 listed Oriental Club was unusual in that during the course of the contract, the building was further extended by the building owner. With tunnelling below at depth, movements set up were considered needed mitigation involving part reconstruction of the cellar and temporary works strengthening and propping.

Building Damage Assessment particulars	Building Damage Assessment practicalities	Instrumentation and Monitoring challenges
Grade 1 listed, four storeys including basement, situated at the end of Stratford Place with existing vaults below Stratford Place at the front and further extended in the past with an eastern wing. Proposed tunnels immediately below at depth where the additional passenger concourse and connections were made to the existing Jubilee line.	Building control archive drawings confirmed that significant extensions have been undertaken over the years, including underpinning of the front façade. Single level vault located into Stratford Place needed strengthening and temporary propping. Became a Railway Protection matter when extended during the course of the works.	Geotechnical instrumentation array and monitoring was in place and was reviewing once the tunnel construction sequence and methodology was confirmed. Supplementary electro levels introduced into the vaults under Stratford Place and along the line of the front façade of the main wing.

Table 7: BDA and I&M practical aspects for The Oriental Club.

5.7 Avon House

Avon House, a 1930s steel framed building, has been written up elsewhere (De Pascali, 2020 and Schoor et al 2021) with selected particular aspects being noted in Table 8.

Building Damage Assessment particulars	Building Damage Assessment practicalities	Instrumentation and Monitoring challenges
Part of the façade was Grade 1 listed, twelve to Five storeys with a single level basement over the footprint of the building and with vaults below Stratford Place at the front. Proposed tunnelling and lifts shafts immediately below the building Extensive array of grouting below to mitigate movements to the building.	Previous consulting engineers records with supplementary Building control archive drawings The footprint of the property consisted of a number of buildings, amalgamated to form a number of retail units and several separate office spaces with a complex mix of foundation bases and beams. Detail sections needed for grouting (Figure 7) In the upper floor with a significant transfer structure introduced at second floor level to open up the office space below.	Geotechnical instrumentation array and monitoring was in place and was reviewing once the tunnel construction sequence and methodology was confirmed. Detailed frame analysis undertaken to develop realistic trigger levels for this significantly modified building, hydrocells introduced during tenant refurbishment during the works to supplement existing instruments.

Table 8: BDA and I&M practical aspects for Avon House

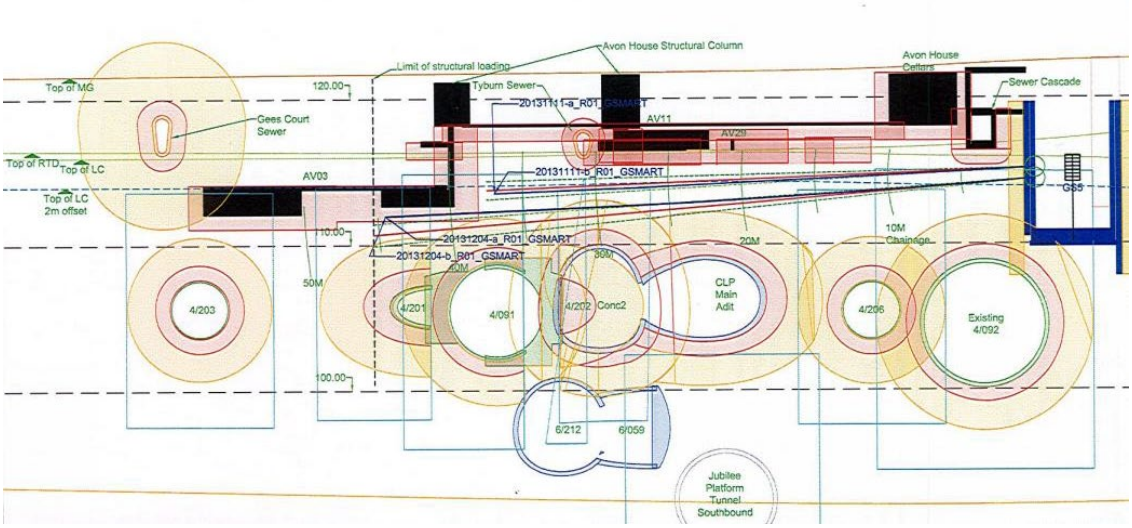

Figure 4: Section through grout line below Avon House foundations (reproduced by kind permission of Bachy Soletanche Ltd)

6. Conclusions

In summary, the main conclusions are:

- Obtain original engineers and / or building control drawings records early in the scheme development, ready for use in Building Damage Assessment
- Undertake a Desktop Structural Appraisal in the third phase, using these drawing records, in association with an inspection, seeking to understand the structural behaviour of the building, it original form and key alterations that change behaviour, such as line load from brick walls amended by inserted frames
- Consider supplementary aspects such as topographical survey, structural investigation and instrumentation. This may include supplementary site investigation if the building is only made vacant at the start of construction and supplementary instrumentation as the building experiences a variery of phases of works such as demolition, grout shaft excavation, ground treatment installation, follow on construction as well as the main phase of tunnelling.

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