Paper Title

A qualitative analysis of the interfaces between urban underground metro infrastructure and its environment in London

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Abstract

As urban environments densify and cities across the world employ urban underground metros for the effective rapid movement of millions of people a day, there is an essential need to ensure the safe continued presence and operation of those metros. To achieve this, the authors argue there is a need for a more detailed qualitative analysis of how urban underground metro infrastructure and its environment interface. Failure to do so could potentially lead to the development of inaccurate asset management data. This would subsequently lead to the implementation of flawed Building Information Modelling processes for 2, 3, and 4D modelling and mapping, of existing and proposed infrastructure.

Following a review of existing asset management approaches which confirms the need for qualitative approaches to the analyses of the interfaces, this paper presents findings from a detailed case study, in the Bayswater area of the City of Westminster in West London, UK. The processes employed for the detailed case study form part of proposed (ultimately) standardised approaches to the gathering, analysis, and sharing, of multi-disciplinary evidence-based data, developed by the authors. Such data is essential to enable effective asset and urban management processes, now and for the future.

Keywords

Railway; Metro; Urban; Underground; Space; London

Highlights

- Interfaces between railway-based infrastructure need to be comprehended
- Railway asset management requires multi-disciplinary evidence-based data
- Multi-disciplinary data gathering assists effective asset management
- The AIR processes provide standardised approaches to data collection and sharing
- The AIR processes contribute to Building Information Modelling processes

1. Introduction

As urban environments densify, globally (United Nations, undated), the use of urban metro systems, to enable the effective mass movement of people, is increasing. Statistics published by UITP (2018), stated that by the end of 2017, 182 cities across the world had a metro system and these collectively carried 168 million passengers a day. To enable the effective safe presence and operation of those metros within their densifying urban environments, it is essential to comprehend how they affect and can be affected by their environment (Durmisevic and Sariyildiz, 2001; Rinaldi, Peerenboom, and Kelly, 2001; Zimmerman, 2004; Besner, 2016). This is necessary not only for the short-term of metro construction or urban redevelopment but effective day-to-day long-term (50+ years) asset and urban management planning and processes (Price et al., 2016; Li, 2019; Von der Tann et al., 2020).

The increasing densification of cities globally and the continuing construction, presence, and operation of urban underground metro systems create what Bobylev, 2009, described as "*rivalness and excludability*" - the needs of one urban stakeholder overriding the needs of other urban stakeholders. Rivalness and excludability are potentially exacerbated by stakeholders not having an effective comprehension of the significance of what, how, when, where, and why interfacing infrastructure affects and are affected by one another (Railway Accident Investigation Branch, 2005; 2014; 2017; 2018).

Through the research of the authors to date, it was identified that there is a current paucity of multi-disciplinary professional and academic discussion on what, how, when, where, and why railway infrastructure interfaces with its contextual environments, in the long-term (Darroch, 2014; 2019; 2020; Darroch, Beecroft, and Nelson, 2016; 2018; University of Aberdeen, 2020a). [1] This appears to be due to current gaps in multi-disciplinary comprehension and discussion of how railway-based systems affect and are affected by their environment. Moreover, there is an apparent lack of sharing of multi-disciplinary evidence-

[1] Where the term multi-disciplinary is employed to mean collective considerations of the legal, civil engineering, geographical (location), transport and urban planning, asset management, and historical natures of railway infrastructure; and the term infrastructure means the basic structure of a metro system or urban environment, which are necessary for its safe presence, operation, or function. Where these can include buildings, tunnels, highways, footways, land, airspace, subsoil, laws, legislation, standards, and property.

based data within organisations and with their interfacing stakeholders (Zimmerman, 2004; Gu, Ergan, and Akinci, 2014; Alnaggar and Pitt, 2019; Abdirad and Sturts Dossick, 2020).

The authors argue, therefore, that there is an essential need for more multi-disciplinary professional and academic consideration and sharing of knowledge, on what, how, where, when, and why those railway-based systems interface with their environment.

Within this paper, Section 2, contextualises the authors' research to date and the topic of this paper, presenting two examples of where lack of shared railway-based and urban stakeholder comprehension of the interfaces had potentially catastrophic circumstances. Section 3, discusses whether current and proposed asset data and urban management processes are sufficient for effective urban interface management. Section 4, presents proposed standardised qualitative processes for gathering, analysing, and sharing multi-disciplinary evidence-based meta-data, relating to the interfaces of railway infrastructure and its environment. These processes enable the development of an asset Interface Register (AIR). Section 5, describes findings from a detailed case study of the interfaces between urban underground metro infrastructure (UUMI) and its environment in Bayswater, London, UK, gained through the application of the AIR processes. Section 6, concludes the paper and its findings.

2. Contextualising the research context

To contextualise this paper, the following section considers two incidents in the UK that led to the disruption of railway services, affecting the journeys of thousands of passengers, and which potentially posed catastrophic risks to staff, passengers, railway-infrastructure, and its environment (Rinaldi, Peerenboom, Kelly, 2001; Starita and Scaparra, 2018). Both incidents included underground or below ground railway infrastructure, their urban environment, and were characterised by a lack of shared multi-disciplinary consideration, of what, where, how, when, and why the railway infrastructure interfaced with its contextual environments. This lack of understanding permeated not only the physical presence, but also legal, asset management, historical, geographical, and urban management considerations.

Fig.1: Auger and debris lying on the track of an underground railway tube tunnel after a tunnel penetration, in 2013. Note the potential for a catastrophic incident to occur if a service train had been passing through the tunnel at the time. **Source:** Railway Accident Investigation Branch, 2014.

Fig.2: Debris lying on the track within a railway cutting, near Liverpool Lime Street station, UK. Note the potential for a catastrophic incident to occur if a service train had been passing through the cutting at the time, with line speeds of 30 and 40mph. **Source:** Railway Accident Investigation Branch, 2017.

The first example (Fig.1), dates from 8 March 2013, when an auger, boring piles for a new development in Central London, UK, penetrated a 110-year-old suburban railway tube tunnel. The subsequent UK Railway Accident Investigation Branch Report (Railway Accident Investigation Branch, 2014), identified that a contributory factor to the incident was a lack of shared multi-disciplinary comprehension of the presence, property, and protection interfaces of the tube tunnel and its environment. Where that lack of shared comprehension was between the owner of the railway infrastructure, its interfacing urban stakeholders (the developer), and representatives of the urban stakeholder (piling contractors, architects, legal practitioners, and urban planners) (Railway Accident Investigation Branch, 2014, p.12).

That lack of comprehension was despite several legal documents indicating that the railway was present 13m below ground level, within the footprint of the proposed development (Railway Accident Investigation Branch, 2014, pp.16-22). Fig.1, shows the augers lying on the track within the tube tunnel amid a pile of gravel, brought through with the penetration. The driver of the train in the background was sent to investigate reports of water pouring into the tunnel.

The second example (Fig.2), dates from 28 February 2017, when part of a stone retaining wall collapsed on to a national mainline railway 20m below ground level, in Liverpool, UK. The land above the retaining wall was leased by the local government authority to an urban stakeholder. Over the 137-year lifetime of the retaining wall, the land above had seen numerous physical changes and uses, such as earthworks and the placement of containers, directly above the wall (Railway Accident Investigation Branch, 2017, pp.15-19). Contributory factors to the collapse were a lack of shared comprehension, between the railway company, the leaseholder of the land above the retaining wall, and the local planning authority, regarding the presence, property, and protection interfaces (Railway Accident Investigation Branch, 2017, pp.15-19). Fig.2 shows the effects of the partial collapse on the mainline railway into Liverpool Lime Street station, which has line speeds of 30 and 40mph.

The findings of the Railway Accident Investigation Branch, for both incidents, clearly demonstrated why it is essential for railway and urban stakeholders to have effective whole life multi-disciplinary evidence-based comprehension of the interfaces. Not only from physical civil engineering considerations, as current discussions suggest are required (Gov.UK, undated(a); Zhou et al., 2019; Yuan et al., 2020), but also from legal, asset management, historical, geographical, and urban management perspectives (International Tunnelling Association, 1991; Zimmerman, 2004; Chrimes, 2006; Atazadeh et al., 2016; Besner, 2016; Network Rail, 2021b).

3. Are current and proposed asset data and urban management processes sufficient?

Prior research by the authors' included a critical review of current literature on asset management and critical systems, of which railway-based infrastructure is an example. Outline and detailed case studies of railway-based infrastructure interfacing with its environment were undertaken (Darroch, 2014; Darroch, 2019; Darroch, Beecroft, and Nelson, 2016; 2018). This has included, discussions with multi-disciplinary stakeholders involved with managing the interfaces of railway infrastructure and its environment (railway companies, utility companies, urban planners) were also undertaken (University of Aberdeen, 2020a).

Current proposals for Building Information Modelling (BIM), 3/4D modelling, and mapping of physical infrastructure and its surrounding environment (International Tunnelling Association, 2000; Peng and Peng, 2018a; 2018b; Gov.UK, undated(a)), are not sufficient for effective current and future transport and urban interface management. This is because those current proposals do not provide railway and urban stakeholders with the multi-disciplinary evidence-based data they require to make effective asset interface decisions (Gu, Ergan, and Akinci, 2014; Alnaggar and Pitt, 2019; Abdirad and Sturts Dossick, 2020; Railway Accident Investigation Branch, 2005; 2014; 2017; 2018).

Moreover, the gathering of multi-disciplinary evidence-based data (Network Rail, 2021b; TfL, undated(a)), to generate the 2, 3, and 4D models and mapping, costs stakeholders considerable time and money through searching for data within many and various sources (Zimmerman, 2004; Gallaher et al., 2004). This has therefore limited the development of multi-disciplinary evidence-based models and mapping of the interfaces for existing infrastructure (Gu, Ergan, and Akinci, 2014; Alnaggar & Pitt, 2019; Abdirad & Sturts Dossick, 2020).

That lack of available combined multi-disciplinary evidence-based data means that stakeholders identify, access, review, employ, and store data in many and various ways, depending on their own needs. Thus potentially leading to the generation of conflicting comprehensions of the interfaces, which can subsequently lead to flawed asset data and subsequent decision-making (Railway Accident Investigation Branch, 2005; 2014; 2017; 2018). This situation is exacerbated by asset interface management being perceived to be primarily a civil engineering consideration, rather than multi-disciplinary (Gu, Ergan, & Akinci, 2014; Institute of Asset Management, 2015; Alnaggar & Pitt, 2019; Abdirad & Sturts Dossick, 2020).

Stakeholders consulted through the research, also stated that they do not necessarily have access to existing multi-disciplinary archival data, know what key multi-disciplinary evidence-based meta-data to look for, or even where to find it. Additionally, where they have gathered meta-data, they do not necessarily make it available across an organisation, or with interfacing stakeholders (McCutcheon and Meredith, 1993; Rinaldi, Peerenboom, and Kelly, 2001; Shenton, 2004; Darroch, 2019; University of Aberdeen, 2020a).

This potentially means that there can be further gaps within asset data management systems, which are used to develop the aforementioned BIM, 2, 3 and 4D modelling and mapping for existing infrastructure (Alnaggar and Pitt, 2019; Abdirad and Sturts Dossick, 2020). Subsequent employment of these models and maps could therefore cause flawed transport and urban strategies, proposals, plans, and policies. This is, however, not acceptable for achieving sustainable urban and interface management within densifying urban environments.

To assist stakeholders to develop effective comprehension of the interfaces and to mitigate the above mentioned risks, the authors developed, tried, and tested qualitative standardised processes of data gathering and sharing (Darroch, Beecroft, and Nelson, 2016; 2018; Darroch, 2019; University of Aberdeen, 2020a). The intention was that the subsequently gathered multi-disciplinary evidence-based meta-data will contribute to current and future management of the interfaces.

4. A qualitative approach to comprehending the interfaces

As identified in Sections 2 and 3, asset, urban, and subsequent asset interface management is data intensive (Li, 2019), due to the legal, engineering, urban, transport, historical, and geographical natures of cities (Bobylev, 2009; Masood et al., 2016; Mohammadi, Amador-Jimenez, and Nasiri, 2019). The data required by railway and urban stakeholders to effectively manage their infrastructure and their interfaces with one another, cannot be wholly dependent on physical considerations, such as civil engineering or the geographical location of an interface (e.g., a utility under a railway) (Gov.UK, undated(a)). It is essential to have a holistic multi-disciplinary overview, as demonstrated by the incidents described in Section 2, and the findings of the Railway Accident Investigation Branch, 2014; 2017.

To confirm this over 50 qualitative analyses of the interfaces between railway infrastructure and its environment, by applying the AIR processes. These consisted of 11 urban underground metro (UUM) and heavy rail systems, in six countries (England x2, Scotland x1, US x2, Brazil x2, China x2, Netherlands x2) (Darroch, 2014; 2019; 2020; Darroch, Beecroft, and Nelson, 2016; 2018).

Within selected organisations, the analyses included: the review of historical and contemporary literature, describing the construction and management of the railway and its environment (Baker, 1885; Badsey-Ellis, 2016; MTR, 2014a; Crossrail, 2019; Strathclyde Partnership for Transport, 2020; Los Angeles County Metropolitan Transportation Authority, 2020); contextual analyses of the interfaces through the consideration of historical and contemporary sources (e.g., historic and current mapping, photographs, and stakeholder asset data); archive data gathering and document review (legal agreements, legislation, engineering drawings and reports, urban planning documentation); outline and detailed case studies; observational analysis; and consultation (semi-structured interviews and discussion) with railway and urban stakeholders (asset managers, civil engineers, legal practitioners, facilities managers; utility companies). Questionnaires of railway-based stakeholders were also undertaken to determine the occurrences of the interfaces and the needs of the stakeholders for multi-disciplinary asset interface data (Darroch, 2019; University of Aberdeen, 2020a).

Through the findings of the research (Darroch, 2014; 2019; 2020; Darroch, Beecroft, and Nelson, 2016; 2018), it was identified that occurrences of presence, property, and protection interfaces between railway infrastructure and its environment, occur internationally. (I.e, where physical infrastructure is present, multiple stakeholders have interests in it, and its safe continued presence and operation must be maintained (Railway Accident Investigation Branch, 2005; 2014; 2017; 2018)). This led to the development of a conceptual framework (CF) (Fig.3), to assist stakeholders in identifying and clarifying the interconnected and interdependent natures of the interfaces and their sub-interfaces (indicated by the directional arrows on the three sides of the CF) (Darroch, Beecroft, and Nelson, 2016). The CF represents the primary interfaces of presence, property, and, and their sub-interfaces, which create or enable the occurrences of the primary interfaces.[2]

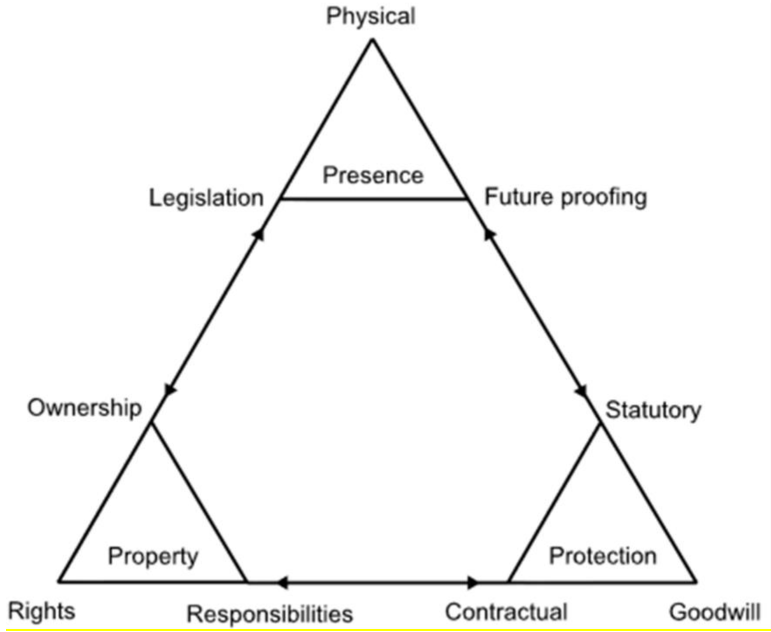

Fig.3: A conceptual framework representing the interconnected and interdependent nature of the interfaces of UUMI and its surrounding environment. Note how each primary interface as contributory sub-interfaces which enable the occurrence of that interface. Source: Darroch, Beecroft, and Nelson, 2016.

As the research progressed, the authors recognised that these principles also applied to other forms of transport infrastructure, urban underground space, and their environment (Darroch, 2019). Moreover, it was recognised that the CF by itself was not sufficient to enable stakeholders undertaking the analyses of the interfaces to gain, analyse, and share the data

[2] The conceptual framework is presented and described in detail within Darroch, Beecroft, and Nelson, 2016.

gathered, in a consistent way. It was also concluded that data would apply not only to the contemporary circumstances of the analyst (e.g., undertaking 1 weeks work of asset maintenance), but the data would also be required for the whole life of the interfaces (50+ years), by many and various other legal, engineering, asset management, and urban planning stakeholders.

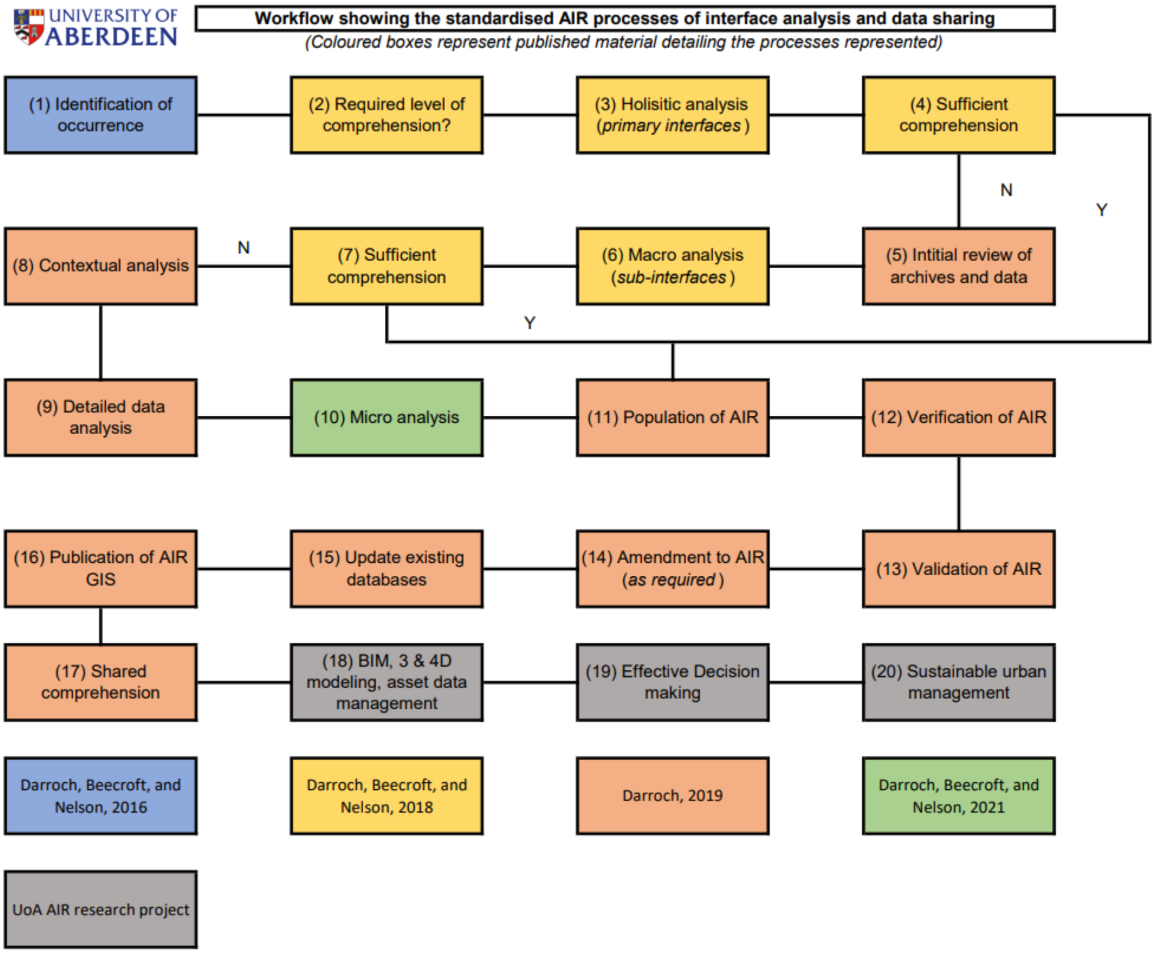

Fig.4: The proposed standardised AIR processes to assist consistent approaches to the gathering, analysis, and sharing of data relative to the interfaces between railway infrastructure and its environment. Note how the AIR processes are to enable the effective gathering and sharing of data to subsequently save organisations time and money, through the generation of multi-disciplinary evidence-based data. The subsequent sharing of that data through a web-based GIS; BIM; 2, 3, and 4D infrastructure and urban modelling, subsequently enables effective decision making for urban management.

The authors, therefore, developed the AIR processes for the gathering, analysis, recording, and sharing of multi-disciplinary evidence-based meta-data. Fig.4, comprises 20 Stages representing the AIR processes and its outputs, starting with identifying an occurrence of the interfaces, Stage 1, described in Darroch, Beecroft, and Nelson, 2016, through to enabling effective urban management Stage 20, reflecting the findings within Railway Accident Investigation Branch, 2005; 2014; 2017; 2018; Gov.UK, undated(d). These processes are intended to assist: standardised consistent approaches to the gathering, analyses, and sharing of multi-disciplinary evidence-based meta-data, by many and various stakeholders. Subsequently contributing towards the development of accurate multi-disciplinary evidence-based BIM, 2, 3, and 4D modelling and mapping of existing and future interfaces. Through these collaborative standardised processes, it is anticipated that enhancements in current and future cost and time savings for railway and urban stakeholders can be achieved. Also, the processes will contribute towards the safe whole-life presence and operation of the railway and urban infrastructure, and their environment, through more effective urban and transport planning and management.

To ensure a standardised consistent approach to undertaking the AIR processes, by many and various stakeholders with different disciplinary interests, skills, knowledge, and experience (Sections 2 and 3), the authors also developed several supporting resources. These include specification of depths of analysis to assist the development of comprehension of the interfaces, subject to the needs of the stakeholder (Stages (3), (6), and (10), Fig.4) (Darroch, Beecroft, and Nelson, 2018); a table of suggested multi-disciplinary tools and resources (CAD/GIS, Archives, etc.), reflecting the need for multi-disciplinary data (Chrimes, 2006; TfL, undated(b); TfL, undated(c)); a table of suggested multi-disciplinary source data (legal agreements, engineering survey drawings, etc.); standardised tables of questions for each depth of analysis that are applied to the CF and source data; and a workflow to assist the application of the proposed standardised processes (Darroch, 2019).[3]

The outputs of the research were collectively named the AIR processes, as they are employed to develop an Asset Interface Register (AIR), which holds the key multi-disciplinary evidence-based data generated from the analysis (Zimmerman, 2004). Completed examples of the AIR, recording the findings from the case study in Section 5, are presented in Appendix

[3] The resources developed for application of the AIR processes are presented and described in detail in Darroch, 2019.

1. Based on the consultations with the railway stakeholders (Sections 2 and 3), it was also identified that it would be beneficial for stakeholders to have access to the multi-disciplinary evidence-based meta-data through a simple to use, easy to access web-based GIS. This resulted in the production of the web-based AIR GIS (University of Aberdeen, 2020b).

Such a web-based GIS would enable the sharing of the AIR data across multi-disciplinary stakeholders, within and externally to a railway organisation, through the minimal use of specialist software, technology, and training. For example, the AIR GIS can be accessed by any stakeholder, using a standard mobile phone, laptop, tablet, or PC, on-site, in a meeting, a café, or at home, with minimal hardware, software, and training (Darroch, 2020). Thus saving organisations time and money through minimising the purchase of specialist technology, software, and training. The data generated within the AIR and represented in the AIR GIS, can, however, be shared through more specialist tools and software.[4]

The following section, therefore, considers Stage (10) of the AIR processes, and the microanalyses of the immediate interfaces between the railway and urban assets forming London Underground and urban infrastructure (buildings, foundations, land, subsoil), within the case study area.

5. A detailed case study of the interfaces, Bayswater, London, UK

The following detailed case study, of UUMI interfacing with its environment on Porchester Terrace, in the Bayswater area of London, formed one of the 50 qualitative analyses of the interfaces between railway infrastructure and its environment (Darroch, 2019), mentioned in Section 4. This enabled the testing of Stages 1-11, of the AIR processes and their supporting resources (Section 4), to determine their applicability and usefulness to asset interface management. This section presents a brief overview of the methods employed for undertaking the case study; findings from the case study; and questions that arose through the authors' research concerning the sufficiency of existing and proposed asset data management, BIM, 2, 3, and 4D mapping and modelling processes, discussed in Sections 2 and 3.

[4] A more detailed discussion of the AIR processes, the supporting resources, and the web-GIS, is available from other works of the authors (Darroch, Beecroft, and Nelson, 2018; Darroch, 2019; Darroch, 2020; University of Aberdeen, 2020a).

5.1 The research methodology

The processes of analysis for the detailed case study followed the qualitative approaches shown within Fig.4, outlined within Section 4, and detailed within Darroch, Beecroft, and Nelson, 2016; 2018; and Darroch, 2019; 2020. As this was to be a detailed case study, Stages (1) to (11), were required to be undertaken. Where the analysis required the application of the supporting resources to the CF and gathered source data (Section 4).

Subsequently, Stage (3), enabled an appreciation of how the UUMI interfaced with its environment. Undertaking Stage (6), allowed an understanding of the immediate interfaces of the UUMI and its interfacing urban infrastructure.[5] Application of Stage (10), the focus of this case study, assisted knowledge development of what, how, when, where, and why the assets forming the UUMI and its interfacing urban infrastructure affected one another. Stage (11), enabled a consistent approach to the gathering and recording of key multi-disciplinary evidence-based meta-data, detailing the contexts of the interfaces, as shown within the tables in the Appendix. An example output of the AIR processes (Stage 16) was also produced, in the form of the web-based AIR GIS (University of Aberdeen, 2020b).

5.2 Gathering data for the detailed case study

Fig.5 shows a Bing maps Streetside image of the case study area within Porchester Terrace, Bayswater, London. The railway, constructed in the mid-1860s, is located within a cutting, the effects of which can still be seen today, 160 years later (centre of the image). To the left centre and rear, and the rear right-hand side of the image, are buildings that pre-existed the construction of the railway (London Transport Museum, 2020a; 2020b). To the centre-right of the image is a row of red brick housing, the subject of the microanalysis, described here. The following describes the undertaking of the microanalysis, within the contexts of presence (Section 5.2.1), property (Section 5.2.2), and protection (5.2.3), with an overview of the detailed case study findings presented in Section 5.3.

[5] Through the review of multiple railway-based organisations information on requirements for consultation where urban redevelopment is proposed, the immediate environment is specified as approximately 30m away from the UUMI (MTR, 2014; Crossrail, 2019; Strathclyde Partnership for Transport, 2020; Los Angeles County Metropolitan Transportation Authority, 2020).

Fig.5: Bing Maps Streetview image showing the surrounding environment to London Underground UUMI forming a cutting (centre of image) in Porchester Terrace, Bayswater, London, UK. The building interfacing with the UUMI and proposed to have a basement level is the red brick building, to the right of the centre. Source: Bing Maps, 2021.

5.2.1 Presence

The processes of analyses for presence at Holistic (Stage (3)) and Macro (Stage (6)) depths (Fig.4) (Darroch, Beecroft, and Nelson, 2018), identified that London Underground had UUMI present within the case study area formed of a tunnel, under the road forming Porchester Terrace, and within an open cut between buildings on the east side of the road (Fig.4).

To develop a knowledge of the presence interfaces, the supporting resources described in Section 4, were applied to the presence interface within the CF (Fig.3). This enabled determination of the most appropriate potential tools and resources, data, and considerations for the presence interface. Once the application of the supporting resources had been made, various archives were accessed to search for, find, and gather, the appropriate data (Chrimes, 2006; TfL, undated(a); undated(b); undated(c); Alnaggar and Pitt, 2019; Abdirad and Sturts

Dossick, 2020).

For the sub-interface of legislation, the following were gathered: the Metropolitan Railway (Notting Hill & Brompton) Act 1864, which authorised construction of the railway; general railway legislation applicable to the purchase of land for railway construction and presence (Land Clauses Consolidation Act 1845 (LCCA 1845)); and requirements for the construction and operation of railways (Railway Clauses Consolidation Act 1845 (RCCA 1845)). Collectively, this legislation contributed to the authors' development of knowledge of what the railway was authorised to do, how land could be bought and sold, and how the interfaces between the railway and its environment affect and are affected by one another in the long-term.

For the physical sub-interface, data was gathered which showed the historical and contemporary occurrences of the physical UUMI and its environment. A historic journal paper, describing the typical nature of cuttings and retaining walls on the railway (Baker, 1885) was found and critically reviewed for any relevant information applicable to the UUMI within the case study area. Detailed London Underground asset survey data in CAD and GIS formats, showing the current physical presence of assets forming the UUMI, were employed to comprehend the current situation. London Underground archive ‘as constructed’ engineering drawings and asset inspection reports, were gathered and reviewed. Thus enabling identification of what UUMI had been constructed, how, when, where, and why, along with any subsequent changes that had been made, over its life-cycle, to date.

As the gathered engineering data did not represent changes made to the environment of the UUMI, as it focused mostly on the UUMI, historic and modern data such as photographs/satellite imagery (London Transport Museum, 2020a; 2020b; Bing Maps, 2021) and mapping (National Library of Scotland, undated; Bing Maps, 2021), were also gathered and reviewed. This enabled the determination of whether the physical interfaces between the assets forming the UUMI and urban assets may have affected one another over their lifetimes to-date. Through the above approaches, no data was found relating to potential methods of future-proofing, as shown within the presence interface in Fig.3.

The findings from the analyses of each occurrence of asset presence were subsequently recorded in the AIR: the retaining wall (Appendix, AIR Table 1); the building and land upon which the building is located (Appendix, AIR Table 2). Additionally, diagrammatic representations of the contemporary and historical natures of the UUMI and its environment were also produced. Where the representations showed modern and historical mapping with the current interfaces overlaid, based on the London Underground CAD and GIS asset survey data.

5.2.2 Property

The processes of analyses for property at Holistic (Stage (3)) and Macro (Stage (6)) depths (Fig.4), identified that London Underground had UUMI property interests within the case study area (TfL, undated(a)). These were formed of freehold ownership of land and airspace within the cutting.

To develop a knowledge of the property interfaces, the supporting resources described in Section 4, were applied to the property interface within the CF (Fig.3). This enabled determination of the most appropriate potential tools and resources, data, and considerations for the property interface. Once the application of the supporting resources had been made, the authors subsequently accessed various archives to search for, find, and gather, the appropriate data (Chrimes, 2006; TfL, undated(a); undated(b); undated(c); Alnaggar and Pitt, 2019; Abdirad and Sturts Dossick, 2020).

For the sub-interface of ownership, data that potentially explained the occurrences of ownership were gathered. However, it was recognised that the data may also contain references to the rights and responsibilities of the interfacing stakeholders. The documentation gathered, was not limited to archival legal records (Conveyance dated 2 July 1873; Conveyance dated 10 July 1930), but also included HM Land Registry documentation, which employed extracts of key data from historical legal agreements (HM Land Registry title and plans: LN108093; LN11590; LN11589; LN11587 (Gov.UK, undated(b)).

Through this combined approach to data gathering, it was identified that there were more legal agreements applicable to the case study area than were first indicated within available data sources (TfL, undated(a); undated(b); undated(c)); or identified through the initial search of the London Underground archives. However, issues with gathering Land Registry data, as with many Cadastre systems across the world, are the necessary access to those systems, the fees payable to gain the required data, and the accuracy of that data (Gov.UK, undated(b); Gov.scot, undated; Kitsakis et al., 2016).[6]

The most surprising finding from the legal data was the identification of the physical presence of a piled ground beam and related ownership, rights, and responsibilities of the urban stakeholder, within subsoil, owned by London Underground, behind the railway retaining wall (Licence, dated 26 January 1945) (Appendix, AIR Table 5). To clarify whether the works had been undertaken for the construction of the ground beam and its supporting piles, a further search of London Underground engineering drawings and reports was undertaken. This revealed that the ground beam and piling solution had indeed been undertaken (discussed further in Section 5.3).

The findings from the analyses of each occurrence of asset property were subsequently recorded in the AIR, adding to the previously gathered presence data (Section 5.2.1). The recorded findings included ownership, rights and responsibilities for: the retaining wall (Appendix, AIR Table 1); the adjacent land, subsoil, building, and its supporting foundations (Appendix, AIR Table 2); substratum interest of London Underground within 10 feet (3.048m), behind the retaining wall (Appendix, AIR Table 3); the fact that the red-brick houses had been constructed with raking piles, which was not identified through the previous presence analyses (Section 5.2.1) (Deed of release and covenant dated 23 January 1936); and contractual protection for the UUMI, which had been imposed on the land forming today's redbrick houses on the south side of the cutting, within the Conveyance of 1930 (Appendix, AIR Table 4).

[6] In the UK, Land Registry data has to be evidence-based and within strict criteria set by the HM Land Registry. HM Land Registry acknowledge there may be gaps in their data, and given the nature of property, the data changes over time. Moreover, the Land register may not show asset ownership, as it is primarily land based (Gov.uk, undated(c)).

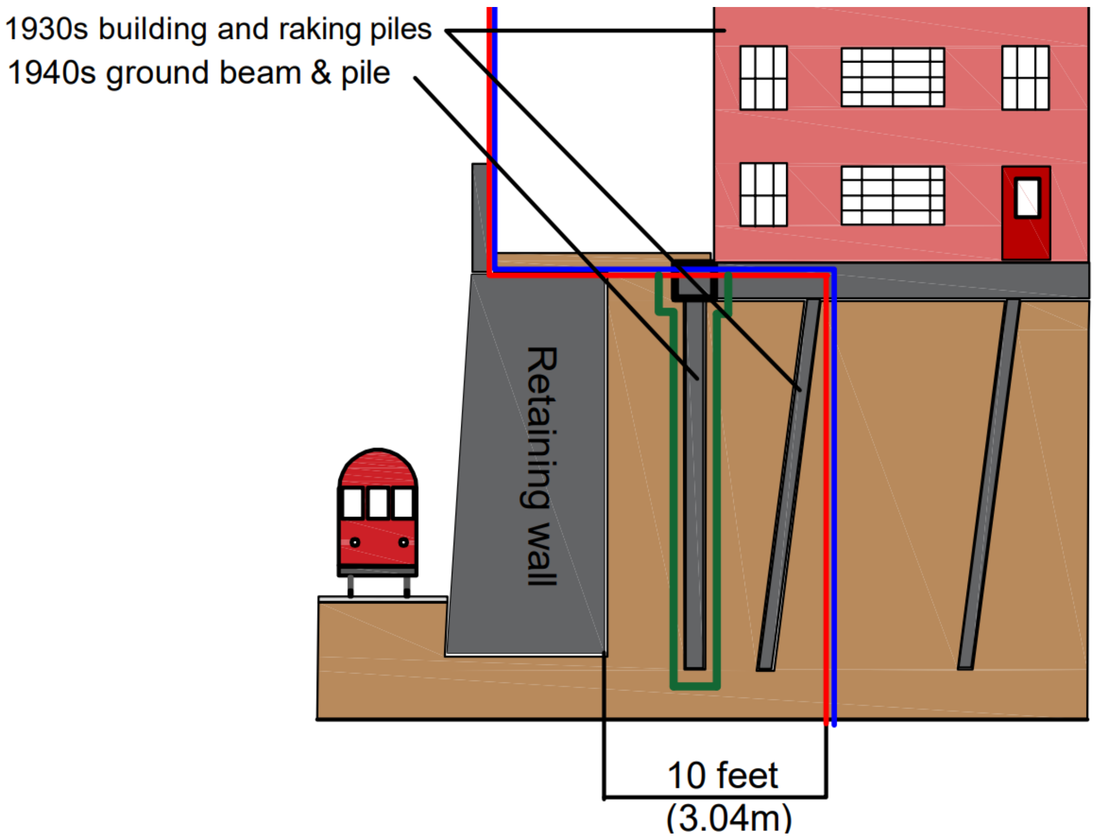

Fig.6: Showing a simplified, not to scale representation of the relationship of the assets forming the UUMI and interfacing urban assets on the south side of the railway cutting, Porchester Terrace, Bayswater, London, UK. The red line represents the extent of the London Underground freehold ownership of land, airspace, and subsoil; the blue line represents the northern extent of the urban stakeholder, and the green outline represents the ground beam and piles permitted to be present within the subsoil of London Underground by the 1945 licence.

From these findings, the diagrammatic representations of the contemporary presence interfaces were modified to also show the additional physical presence and property natures of the interfacing UUMI and its environment. Based on the microanalyses of the property interfaces, the simplified diagram within Fig.6, was produced, to represent the current occurrences of the interfaces, below ground level. To represent the findings of the property analyses within its contextual environment, the property data gathered was also represented within the AIR GIS (University of Aberdeen, 2020b). Fig.7, is an extract from the AIR GIS with coloured and stylised lines and shapes representing the physical, property, and protection interfaces of the UUMI and its environment, within the case study area (Sections 2 and 3)

(Darroch, 2019; Darroch, 2020). [7]

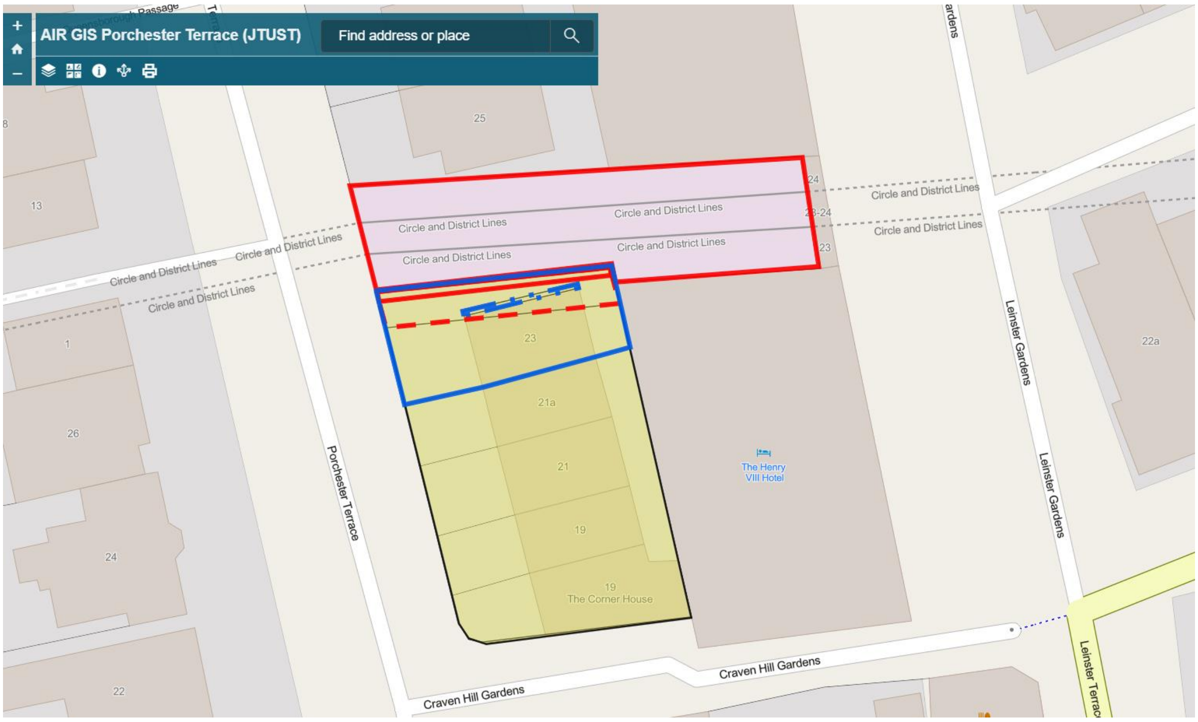

Fig.7: Showing an extract from the AIR GIS, and the identified occurrences of presence, property, and protection within the case study area. The coloured and various outlined shapes represent solid red - London Underground land, structures (the retaining wall), and airspace; solid blue - urban stakeholder land, airspace and infrastructure; dashed red - the approximate extent of the London Underground owned subsoil; dashed double dot blue - the indicative location of the ground beam; shaded yellow - the land upon which contractual protection applies. In the AIR GIS, shapes can be interrogated at the click of a button to see the meta-data held within the AIR (e.g., the tables in the Appendix). Source: University of Aberdeen, 2020b.8

5.2.3 Protection

In the discussion on presence (Section 5.2.1), it was noted that the review of legislation authorising the construction, presence, and operation of the UUMI, had not identified any future-proofing requirements for the UUMI, urban infrastructure, or its environment, within the case study area. However, the microanalyses of the historical property data (Section 5.2.2), identified that the land forming the red-brick houses on Porchester Terrace, adjacent to the UUMI, did contain contractual protection for the UUMI (Fig.3).

As discussed in the section on property (Section 5.2.2), however, the identification of the

[7] The reader can use the interactive web AIR GIS, through the link within the references to this paper. An additional case study site is also available of Smithfield Meat Market and environs, London, UK, by searching for ‘Charterhouse Street’, in the GIS location search function.

[8] Readers can access the AIR GIS through the University of Aberdeen, 2020b, link provided in the references. Another case study is also available. Search for “*Charterhouse Street, London*”, in the GIS “*Find address or place*” function in the GIS.

occurrence of contractual protection was only available through the gathering of various primary legal sources (Conveyance, dated 2 July 1873; Conveyance, dated 10 July 1930; Deed of release and covenant, dated 23 January 1936; Licence, dated 26 January 1945); and secondary source legal documents (HM Land Registry title and plans: LN108093; LN11590; LN11589; LN11587 (Gov.UK, undated(b)).

Without the gathering and review of the legal documentation, which contained multi-disciplinary (engineering, legal, historical, transport, and urban planning) data, the determination of the contractual protection would not have been identified, nor would it be possible to produce Figs.6 and 7. Thus demonstrating the need for combined standardised approaches to multi-disciplinary evidence-based data gathering, recording, and sharing, to enable effective interface management. These findings, therefore, reflect those presented in Sections 2, 3, and 4, and as stated as a need by railway-based stakeholders, as part of the authors' research to date (Darroch, 2019; University of Aberdeen, 2020a). The following section presents the collected findings from the microanalyses, achieved through the application of the AIR processes and their supporting resources (Section 4).

5.3 Findings from the microanalyses

It is not possible within the limitations of this paper, to provide a detailed discussion of the findings from the case study. As such, the following presents an overview of the findings, from the microanalyses, which employed Stages (1) to (11) and (16) of the AIR processes, and its supporting resources. More detailed findings can be found within the AIR Table data within the Appendix, and the web-based AIR GIS (University of Aberdeen, 2020b).

Through the analyses, it was found that the construction of the railway was authorised by the Metropolitan Railway (Notting Hill & Brompton) Act 1864. The Act incorporated clauses from the LCCA 1845 and the RCCA 1845. Collectively, these Acts stipulated processes for land appropriation and the requirement for the railway company to accommodate existing urban infrastructure (roads, utilities, etc).

Due to the use of steam locomotives on the railway, which at this location climbs eastwards, a ventilation shaft (blast hole) was required (outlined red, in Fig.7) (Baker, 1885). In 1873, the

Metropolitan Railway purchased land on the east side of Porchester Terrace, for the construction of the cutting. Due to clauses within the LCCA 1845, an additional quantity of land, not required for the cutting, had to be purchased (shaded yellow, outlined black). Demolition of property to the eastern (Leinster Gardens) end of the cutting was then undertaken (London Transport Museum, undated(a); undated(b)). Demolition on the land within the case study area (now forming the cutting and the red-brick houses on Porchester Terrace (outlined red and black, shaded yellow) was not required as this was a garden for a single large house (Conveyance, dated 2 July 1873; National Library of Scotland, undated). However, a retaining wall for the cutting was partly constructed within the land shaded yellow, outlined black (Fig.6, and outlined red in Fig.7).

As the remainder of the land, shaded yellow, outlined black, was not required by the railway, it was sold in 1930. However, excluded from the disposal by the railway company, was all subsoil within 10 feet (3.048m) behind the retaining wall (Fig.6, and dashed red in Fig.7). This was retained by the railway company to protect the UUMI from any future urban development (Conveyance, dated, 10 July 1930). Moreover, contractual protection for the UUMI was imposed on the land to further ensure the safe continued presence and operation of the UUMI. The Conveyance, therefore, obliged the purchaser, and any consequent landowner, in perpetuity, to consult with and gain the permission of the railway company for any works of construction and demolition on the land. This has resulted in London Underground, as the successor to the company which built the railway, having presence, property, and protection interests within the interfacing urban land.

By 1936, the interfacing urban stakeholder wished to demolish the single house, within the land shaded yellow, outlined black, and erect the current red-brick houses. The proposal required a new legal agreement, between the landowner and the railway company, to permit the works to be undertaken (Deed of release and covenant, dated 23 January 1936). The 1936 agreement was in addition to, and not to replace, the existing 1930 agreement. Drawings within the 1936 agreement also showed additional presence information, which had not been identified through the presence analyses (Section 5.2.1). In that the new red-brick houses were constructed on raking piles, to minimise surcharge on the retaining wall, due to the previously undeveloped nature of the former garden land.

Due to the movement of the retaining wall, supporting the land shaded yellow, outlined black, by 1945, possibly due to bomb damage in the second world war, additional foundations were required for the red-brick house closest to the UUMI. The new foundation system was to be located within the subsoil retained by the railway company, through the 1930 conveyance. Not only was there a requirement to gain the railway companies permission for the works, under the 1930 and 1936 agreements, but the Company also had to grant permission for the presence of the new foundations within their subsoil. This resulted in a new legal agreement for the placement of a ground beam and vertical piles, along the north side of the building, adjacent to the retaining wall (Fig.6) (Licence, dated 26 January 1945).

Whilst these are historical events, it is apparent that the presence, property, and protection interfaces of the UUMI and its environment continue to affect one another today (Fig.6 and 7) and will continue to do so for as long as the UUMI and the land are in use. However, as can be seen from the discussion of the case study (Section 5.2), to identify these long-term occurrences, many and varied archives and different sources of data had to be identified, gathered, interpreted, and findings recorded. The authors argue that this demonstrates the concerns of the railway stakeholders, internationally, who were consulted as part of their research, to date (Sections 2, 3, and 4). Moreover, the findings support the arguments of current global literature on asset data management (Zimmerman, 2004; Gallaher et al., 2004; Gu, Ergan, and Akinci, 2014; Railway Accident Investigation Branch, 2005; 2014; 2017; Alnaggar and Pitt, 2019; Abdirad and Sturts Dossick, 2020).

Two questions, therefore, arise, based on the topics presented in this paper. First, are current asset and urban data management processes, for comprehending the interfaces, sufficient? Second, are internationally proposed improvements to asset data management, through the implementation of BIM, 2, 3, and 4D modelling, and mapping (Gov.UK, undated(a); Acheampong and Silva, 2015; RICS, 2019; Zhou et al., 2019), also sufficient to ensure the sustainable safe presence and operation of UUMI within densifying urban environments?

6. Conclusion

The findings from the detailed case study presented within this paper, demonstrate that UUMI, as representative of other railway infrastructure and its environment, has multi-disciplinary presence, property, and protection interfaces. These interfaces must be effectively comprehended at different depths of analysis, suitable to the needs of many and various railway and urban stakeholders, as evidenced by the two examples in Section 2. They are not peculiar to London or even the UK, findings of the authors' research to date have identified they occur across the world, and with other forms of transport infrastructure (Darroch, 2019).

Comprehension of the interfaces requires the collection, analysis, and comprehension of many and various types of multi-disciplinary data (Sections 2, 3, 4, and 5). Through the research (Darroch, 2014; 2019; 2020; Darroch, Beecroft, and Nelson, 2016; 2018; University of Aberdeen, 2020a), it was identified that railway and urban stakeholders have no standardised approaches to the gathering of multi-disciplinary evidence-based data, analysis of that data, or proposals for the effective sharing of interface meta-data. This is despite the stakeholders consulted, stating that they have many and various needs, interests, skills, knowledge, experience, or access to different specialist technologies and software. Findings therefore suggest that the proposed standardised AIR processes of data gathering, analysis and sharing would be beneficial to railway and urban stakeholders, internationally.

This is because, the densification of urban environments globally (United Nations, undated), creates occurrences of "*rivalness and excludability*" (Bobylev, 2009), which last for generations. The authors hope, therefore, that the application of the proposed standardised AIR processes, shown in Fig.4, will be a beneficial method for standardised multi-disciplinary evidence-based data gathering, analysis, and sharing, through rigorous, consistent, uniform, principles of conduct.

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Appendix – The populated AIR tables

Asset ref. no.	LU ref. W263
AIR ref. no.	N/A
Location code	LU ref. D122
Type of asset	Retaining Wall
Between or at key locations	Bayswater – Paddington
Asset description	Mass concrete retaining wall constructed c.1867, with brick facia, supporting southern side of cutting
Specific site	Subjacent to 23 Porchester Terrace, Bayswater
Local authority	City of Westminster
Owner	London Underground
Other party ref. no.	N/A
Maintainer	London Underground
Rights and responsibilities	London Underground owns and is responsible for the maintenance and repair of the retaining wall
Reasoning	The wall was constructed with the Circle line, c.1867, to provide a ventilation shaft
Legislation	Metropolitan Railway (Notting Hill & Brompton) Act 1864
Primary sources	Conveyance, dated 2 July 1873, between The Trustee Lessees of The Paddington Estate & the Ecclesiastical Commissioners for England and the Metropolitan Railway (TfL Muniments: 1056273); Baker, B., 1885. The Metropolitan and Metropolitan District Railways. *Proceedings of the Institution of Civil Engineer*, [e-journal] 81 (1885), pp. 1-33. Available through: ICE Virtual Library <https://doi.org/10.1680/imotp.1885.21367>
Secondary sources	Method Statement, 1990. D122 W262 & W263 Porchester Tce., 0000005047. Held within TfL Documents Manager; Report, 11 June 1993. Correspondence-0000127378-0. Held within TfL Documents Manager.
Notes	See Fig.6 for a diagrammatic representation of the interface

Appendix, AIR table 1: showing the key evidence-based data relative to the UUMI forming a retaining wall.

Asset ref. no.	Previously unrecorded
AIR ref. no.	AIR-D122-4
Location code	LU ref. D122
Type of asset	Land, subsoil, building, and foundations
Between or at key locations	Bayswater – Paddington
Asset description	Land, subsoil, building, and 17in (0.43m) 15-degree angle raked piled foundations, forming 23 Porchester Terrace
Specific site	23 Porchester Terrace, Bayswater
Local authority	City of Westminster
Owner	Owner of 23 Porchester Terrace/London Underground
Other party ref. no.	N/A
Maintainer	Owner of 23 Porchester Terrace/London Underground
Rights and responsibilities	The owner of 23 Porchester Terrace owns and is responsible for the building, land, piled foundation (including AIR-D122-2) supporting their building, and the subsoil under their property (in excess of 10ft (3.048m) behind retaining wall W263 and not forming AIR-D122-1), the owner is responsible for not surcharging the land, and must gain written approval of London Underground for any works to their property; London Underground owns and is responsible for the subsoil (ref. AIR-D122-1) within 10ft (3.048m) behind retaining wall W263 and under the building forming 23 Porchester Terrace, London Underground must approve in writing any proposed works on the land as described in AIR-D122-3
Reasoning	The land forming 23 Porchester Terrace was sold, by the railway company, with limitations on subsoil ownership and restrictions imposed upon use of the land, through a Conveyance, dated 10 July 1930, permission was granted by the railway company in 1936 to erect 19-23 Porchester Terrace, in accordance with the restrictions within the Conveyance of 1930 and the Deed of release and covenant of 1936;
Legislation	Metropolitan Railway (Notting Hill & Brompton) Act 1864; Land Clauses Consolidation Act 1845
Primary sources	Conveyance, dated 2 July 1873, between The Trustee Lessees of The Paddington Estate & the Ecclesiastical Commissioners for England and the Metropolitan Railway (TfL Muniments: 1056273); Conveyance, dated 10 July 1930, between the Metropolitan Railway Company and Gavin Parker-Ness (TfL Muniments: 1015184); Deed of release and covenant dated 23 January 1936, between the Metropolitan Railway Company and Gavin Parker-Ness. (TfL Muniments: 1015186); Licence, dated 26 January 1945, between the London Passenger Transport Board and Sir Lindsay Parkinson Holdings Ltd and Royal Exchange Insurance (TfL Muniments: 1015189)
Secondary sources	HM Land Registry title and plans: LN108093; LN11590; LN11589; LN11587
Notes	See Fig.6 for a diagrammatic representation of the interface

Appendix, AIR table 2: showing the key evidence-based data relative to the land, subsoil, building, and foundations of 23 Porchester Terrace.

Asset ref. no.	Previously unrecorded
AIR ref. no.	AIR-D122-1
Location code	LU ref. D122
Type of asset	Substratum
Between or at key locations	Bayswater – Paddington
Asset description	Subsoil, excluding surface and piled ground beam (AIR-D122-2), up to 10ft (3.048m) behind retaining wall W263
Specific site	Subjacent to 23 Porchester Terrace, Bayswater
Local authority	City of Westminster
Owner	London Underground
Other party ref. no.	N/A
Maintainer	London Underground/Owner of 23 Porchester Terrace
Rights and responsibilities	London Underground owns the subsoil up to 10ft (3.048m) behind retaining wall W263, and is responsible for supporting the land forming 23 Porchester Terrace (AIR-D122-4); the owner of 23 Porchester Terrace is responsible for not surcharging the land and must gain written approval of London Underground for any works to their property
Reasoning	The land forming 23 Porchester Terrace was sold, by the railway company, with limitations on subsoil ownership and restrictions imposed upon use of the land, through a Conveyance, dated 10 July 1930
Legislation	Metropolitan Railway (Notting Hill & Brompton) Act 1864; Land Clauses Consolidation Act 1845
Primary sources	Conveyance, dated 2 July 1873, between The Trustee Lessees of The Paddington Estate & the Ecclesiastical Commissioners for England and the Metropolitan Railway (TfL Muniments: 1056273); Conveyance, dated 10 July 1930, between the Metropolitan Railway Company and Gavin Parker-Ness (TfL Muniments: 1015184); Deed of release and covenant dated 23 January 1936, between the Metropolitan Railway Company and Gavin Parker-Ness. (TfL Muniments: 1015186); Licence, dated 26 January 1945, between the London Passenger Transport Board and Sir Lindsay Parkinson Holdings Ltd and Royal Exchange Insurance (TfL Muniments: 1015189)
Secondary sources	HM Land Registry title and plans: LN108093; LN11590; LN11589; LN11587
Notes	See Fig.6 for a diagrammatic representation of the interface

Appendix, AIR table 3: showing the key evidence-based data relative to the urban environment formed of subsoil adjacent to the retaining wall and under 23 Porchester Terrace.

Asset ref. no.	Previously unrecorded
AIR ref. no.	AIR-D122-3
Location code	LU ref. D122
Type of asset	Covenants on land [legal agreement]
Between or at key locations	Bayswater – Paddington
Asset description	Covenants imposing limitations and restrictions on land and subsoil forming 19-23 Porchester Terrace
Specific site	At ground level and subjacent to 19-23 Porchester Terrace, Bayswater
Local authority	City of Westminster
Owner	London Underground
Other party ref. no.	N/A
Maintainer	Owners of 19-23 Porchester Terrace/London Underground
Rights and responsibilities	The owners of 19-23 Porchester Terrace must gain written approval of London Underground for any works to their property; London Underground possesses covenants on the land and subsoil forming 19-23 Porchester Terrace, owns the subsoil up to 10ft (3.048m) behind retaining wall W263, and is responsible for supporting the land forming 19-23 Porchester Terrace
Reasoning	The land was sold through a conveyance, dated 10 July 1930, within which contractual protection for the railway infrastructure was imposed on the sold land
Legislation	Metropolitan Railway (Notting Hill & Brompton) Act 1864; Land Clauses Consolidation Act 1845
Primary sources	Conveyance, dated 2 July 1873, between The Trustee Lessees of The Paddington Estate & the Ecclesiastical Commissioners for England and the Metropolitan Railway (TfL Muniments: 1056273); Conveyance, dated 10 July 1930, between the Metropolitan Railway Company and Gavin Parker-Ness (TfL Muniments: 1015184)
Secondary sources	HM Land Registry title and plans: LN108093; LN11590; LN11589; LN11587
Notes	

Appendix, AIR table 4: showing the key evidence-based data relative to the contractual protection imposed on the land and subsoil forming 19-23 Porchester Terrace.

Asset ref. no.	Previously unrecorded
AIR ref. no.	AIR-D122-2
Location code	LU ref. D122
Type of asset	Building foundation
Between or at key locations	Bayswater – Paddington
Asset description	Ground beam and piled foundation under 23 Porchester Terrace, adjacent to W263
Specific site	Subjacent to 23 Porchester Terrace, Bayswater
Local authority	City of Westminster
Owner	Owner of 23 Porchester Terrace/London Underground
Other party ref. no.	N/A
Maintainer	Owner of 23 Porchester Terrace/London Underground
Rights and responsibilities	The owner of 23 Porchester Terrace owns and is responsible for the ground beam and piled foundation, the owner is responsible for not surcharging the land, and must gain written approval of London Underground for any works to their property; London Underground owns the subsoil (AIR-D122-1) up to 10ft (3.048m) behind retaining wall W263 and is responsible for supporting the land forming 23 Porchester Terrace.
Reasoning	The ground beam and piled foundation were constructed in 1945, by the then owner of 23 Porchester Terrace, due to ground movement. The ground beam and pile are present through a Licence, dated 26 January 1945.
Legislation	Metropolitan Railway (Notting Hill & Brompton) Act 1864; Land Clauses Consolidation Act 1845
Primary sources	Conveyance, dated 2 July 1873, between The Trustee Lessees of The Paddington Estate & the Ecclesiastical Commissioners for England and the Metropolitan Railway (TfL Muniments: 1056273); Conveyance, dated 10 July 1930, between the Metropolitan Railway Company and Gavin Parker-Ness (TfL Muniments: 1015184); Deed of release and covenant dated 23 January 1936, between the Metropolitan Railway Company and Gavin Parker-Ness. (TfL Muniments: 1015186); Licence, dated 26 January 1945, between the London Passenger Transport Board and Sir Lindsay Parkinson Holdings Ltd and Royal Exchange Insurance (TfL Muniments: 1015189)
Secondary sources	N/A
Notes	

Appendix, AIR table 5: showing the key evidence-based data relative to the ground beam and piled foundation supporting 23 Porchester Terrace.