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Generation of a building typology for risk assessment due to urban tunnelling

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ABSTRACT: Major underground infrastructure projects are often located beneath dense urban environments in an effort to relieve congested areas. The effects of urban tunnelling works can impinge on hundreds, if not thousands of structures, many of which are historically significant. Tunnel-induced ground movements can result in significant building damage and, therefore, require an accurate risk assessment of the existing built heritage and the selection of appropriate preventative measures. Damage prediction techniques extend from traditional empirical and analytical methods to modern computational modelling techniques. A common requirement for many damage assessment methodologies is the development of a building typology. Such typologies can provide critical information where measured drawings, particularly of structural elements (e.g. floor and wall thickness), are not otherwise available. This study begins to establish a building typology for a historic area of Dublin's city centre for which an underground railway system has been planned.

KEY WORDS: Tunnelling; Building Damage; Risk Assessment; Building Typology.

1 INTRODUCTION

A rapid railway system, Metro North, has been granted planning permission in Dublin, Ireland.¹ The initial 5.5km is routed beneath a portion of Dublin's city centre, which currently holds nomination for UNESCO World Heritage Status (Figure 1).²

Figure 1. Study Area

This paper examines the study area outlined in Figure 1 with a view to categorically determining the nature of the built environment to assist in damage prediction from tunnel subsidence. This region contains a high number of historic buildings, with the majority of this region forming an Architectural Conservation Area.³ Since damage prediction techniques often focus on individual buildings, the development of a building typology is commonly employed as part of risk assessments for large projects of this nature. This can provide engineers with a basis upon which to make design assumptions where individual building information is unavailable. Such an effort is initiated in this paper; the importance of which is significant as measured drawings are not available for the majority of the structures and those that are available more often focus on architectural elements than items of structural concern.

2 BACKGROUND

2.1 Damage Prediction Methods

Risk assessments for structures subject to adjacent tunnelling works employ a variety of methodologies. Procedures range from empirical methods based on observed limits to modern numerical methods, which can fully account for the soil-structure interaction. However, what is common to all methodologies is the need for building information. Traditionally, prediction methods for buildings subject to tunnelling works, were estimated based on empirical methods relating to ground settlements and according to a greenfield scenario, whereby the presence of the building is neglected. Peck⁴ idealised the resulting settlement trough at ground level according to a Gaussian distribution. This profile was later extended to the case of twin tunnels by New and O'Reilly.⁵ Damage limits were subsequently employed, such those proposed by Skempton and MacDonald⁶ and Rankin,⁷ which were based on building dimensions and tunnel layout.

The concept of critical tensile strain, whereby the onset of visible cracking for a building was associated with a value of tensile strain, was introduced by Polshin and Tokar,⁸ thereby incorporating building material properties into the discussion. Burland and Wroth⁹ employed this concept in their analytical methodology where the building was idealised as a deep, elastic, simply-supported beam and the critical tensile strain calculated. This concept was later extended by Boscardin and Cording¹⁰ to account for the effects of horizontal strain.
With the recent advancements in computing technology, numerical modelling of the problem has become increasingly popular. Whilst both empirical and analytical methods tend to examine the ground and the building independently, the use of computer modelling enables the soil–structure interaction to be addressed. A study by Potts and Addenbrooke revealed a reduction in greenfield settlements due to building stiffness through the use of two-dimensional (2D) finite element modelling of the soil and adjacent building.

2.2 Dublin's Built Environment

A variety of literature is available relating to Dublin's built heritage, but that related to the vernacular structures that comprise the bulk of Dublin's architectural fabric is highly limited. For example, in Casey's seminal work on Georgian Dublin, the greater portion of this text describes public buildings, including religious buildings, monuments and sculpture. Only limited sections are included on traditional domestic architecture, and that which is included relates mainly to the larger castles and townhouses.

The more common terraced house consisting of brickwork of Georgian Dublin, is described in limited detail as being built in large numbers from the 1720s onwards. Houses of the C18th generally consisted of three of four storeys over a basement. For some structures Casey provides details of individual street buildings including construction dates, building materials, and façade detailing, but little else.

There are a few other resources. Publications by the Dublin Civic Trust relating to specific street addresses provide further building information including: year of construction; number of storeys; building material; façade ornamentation; repair details; and interior details. Furthermore, databases such as Historic Ireland's Building Environment and Road Network Inventory Access (HIBERNIA) provide a means for gathering large amounts of data relating to Ireland's built environment. While there does exist a National Inventory of Architectural Heritage (NIAH) devoted to identifying and recording the architectural heritage of Ireland from 1700 until present, this has yet to be conducted for the region of Dublin.

Although these sources provide a framework for the creation of a building typology, most lack relevant structural information. Dublin City Council's website contains measured drawings for buildings for which planning permission had recently been sought. However, these documents are limited to requests which were sought since 2005 and are inconsistent in both their quality and the level of detail provided.

3 SCOPE AND METHODOLOGY

Thus, to date the resources have not been readily available to generate building typology. This study attempted to overcome this through an extensive field investigation. Within the proposed study area, 449 individual buildings were identified within Figure 1. Data collection involved a combination of fieldwork, image collection, and archival investigation. Physical building attributes were primarily sought.

Measured drawings of some type were available for 27.6% of the dataset. These mainly provided building heights, widths, lengths and number of basement levels. Where measured drawings were not available, estimates were made based upon fieldwork. This involved the creation of an image collection, whereby the front façade of each building was photographed. Not only did this provide a means for visually analysing each of the buildings in the study area, it also acted as a historical record.

A range of building attributes were sought in order to generate the building typology. Since the purpose of the typology in this instance is for risk assessment due to adjacent construction works, physical building properties were primarily sought. Specifically, risk assessments in the case of ground movements tend to examine structural building properties relating to material behaviour, building dimensions, and percentage of openings. Architectural properties were also examined, which included year of construction, architectural details, window shapes and architectural classification. Furthermore, specifically relating to the proposed project, building location and respective orientation in relation to the tunnel were sought.

4 RESULTS

This section will present a classification of the 449 buildings examined according to the main physical and architectural findings. Items relevant to general building typologies are introduced first, while more project specific items are presented subsequently.

4.1 Year of Construction

Dates of construction were sought since this information can often serve as an indicator of building composition and its attendant structural system. The year of construction was obtained for 42% of the buildings. The majority (37% or 70 buildings) are shown to have been built in the first half of the C20th (Figure 2). Significant proportions were built in the latter half of the C18th (17%) as well as the latter half of the C19th (23%).

![Figure 2. Year of Construction](image)

4.2 Building Material

Eight main exterior building finishes were identified (Figure 3). Figure 4 shows their distribution within the study area. Overall, 91% of the study area consists of masonry. A further 4% consist of a rendered façade. However, judging by the configuration of these buildings, it would seem reasonable to assume that these buildings also consist of masonry. Brickwork was the predominant building material of Dublin architecture throughout the C18th and the majority (67%) of buildings in the study area are exclusively of brickwork. Heavier cut ashlar and stone appears to dominate more prominent buildings, often ecclesiastical or public in nature.
4.3 Number of Building Storeys

Four-storey structures predominated, typifying 62% of the buildings (Figure 5). These mainly consisted of terraced masonry buildings which, in the past, formed the bulk of Dublin’s domestic architecture. Nowadays however, the majority of these buildings are commercial spaces, with shop fronts at the ground level.

Figure 5. Number of Storeys

4.4 Building Dimensions

Figure 6 illustrates the distribution of building dimensions for the full study set. The typical building is 11-15m in height, less than 5m wide, and 6-10m long. Thus, slender buildings with relatively small footprints predominate the study area.

Figure 6. Building Dimensions

4.5 Floor and Wall Thickness

Floor thickness information was available for 11.4% of the buildings and wall thickness for 10.2% of them. The predominant floor thickness varied between 300 and 349mm, while the most prevalent wall thickness exceeded 400mm (Figure 7).
4.6 Opening Ratio

Many studies have examined the influence of openings in walls since this may control the overall building stiffness. Opening Ratio (OR) may be defined as the ratio of the total area of openings (including windows and doors) to the total possible wall area of solid wall (see Equation 1).

\[
OR = \frac{\text{Area}_{\text{openings}}}{\text{Area}_{\text{wall}}} \quad (1)
\]

Figure 8 reveals the distribution for the full study area where opening ratios of 0.3 (26% or 115 buildings) and 0.4 (22% or 100 buildings) predominate for the front façades; notably most of the buildings have at least one party wall and are generally inaccessible from the back.

4.7 Basement Levels

Information regarding basement levels was available for 77 buildings, just 17% of the study area. Of these, 81.8% had a single basement level, 10.4% had a double basement, and the remaining 7.8% had no basement.

4.8 Foundation Type

Foundation type was identified for just 17 buildings (only 3.8% of the study area). Of these 67% had raft foundations, 25% strip foundations, and the remaining 8% piled foundations. The identification of foundation type is important, particularly with regard to building response to ground movement, as is the case for tunnelling works. In general, buildings founded on deep foundations are more likely to undergo deformation since the bearing level of the foundation elements is closer to the tunnel's crown. However, the extent of deformation depends on the building's location with respect to the tunnel.

4.9 Architectural Detailing

Significant ornamentation was identified for 22% of the buildings (Figure 9a). Minor ornamentation was noted for 12% (Figure 9b), and the remaining 66% possessed no ornamentation (Figure 9c).
4.10 Window Shape

The typical windows for most of the buildings (81% or 364 buildings) were rectangular (Figure 11a). Another 11% (50 buildings) contained arch-shaped openings (Figure 11b) and just 1% (2 buildings) included wedge-shaped openings (Figure 11c). For the remaining 7% (33 buildings), window shape was not relevant for the following reasons: the building façade contained no window openings; the building consisted of window decorative structures where opening shape is difficult to determine (Figure 12); or the building consisted of a framed structure.

![Window Shape](image)

Figure 11. Window Shape

![Window Decorative Structure](image)

Figure 12. Window Decorative Structure

4.11 Architectural Significance

Dublin City Council (DCC) classifies 43% of the study area (193 buildings) as protected structures. The study area is also classified by DCC according to land usage. Four distinct zones were designated: 1) residential with mixed use; 2) commercial, retail, business use; 3) educational, institutional, community, civic use; 4) car parks. The distribution of buildings in the study area is illustrated in Figure 13, where the vast majority of buildings (90%) are now commercial.

![Land Usage](image)

Figure 13. Land Usage

4.12 Building Orientation and Respective Location

Building orientation and location do not generally form part of traditional building typologies. However, since this purpose of this building typology is for risk assessment for tunnelling works, consideration of a building's orientation and location relative to the tunnel is relevant.

Buildings that have their front façade lying approximately parallel to the tunnel axis (Figure 14, location A) account for 52% of the study area (233 buildings). The remaining 48% of the study area (216 buildings) lie with their front façade perpendicular to the tunnel axis (Figure 14, location B). The latter orientation is generally considered more vulnerable, as will be described below.

![Building Orientation](image)

Figure 14. Building Orientation

Tunnel-induced ground movements result in a variety of modes of building movement. In general, buildings subject to the hogging mode are more susceptible to damage. Particularly for masonry structures, this is the case due to their low tensile capacity. The proposed project examined as part of this study is for twin tunnels. Since narrow structures are primarily of interest as part of this study, four main building locations were examined, as illustrated in Figure 15.

![Building Location within Settlement Trough](image)

Figure 15. Building Location within Settlement Trough

For the buildings located greater than 30m away from the nearest tunnel (54.8% of study area), settlement effects are assumed to be negligible since the generated settlement trough
at ground level generally does not exceed a 30m distance from the tunnel axis, as derived from the Environmental Impact Statement. The majority of these buildings (154 buildings) are shown to be positioned in the hogging mode (location D). A significant number is also shown to be positioned in location C (31 buildings). These building locations are arguably the most vulnerable, particularly for masonry structures whose material properties cannot withstand tensile forces. For those positioned in either location C or D, 59% (109 buildings) are placed in orientation A (see Figure 14) while 41% (76 buildings) are situated in the more vulnerable orientation B.

From the above results, it would appear that the most common building for the study area is a four storey brickwork structure between 11 - 15m in height, roughly 5m in width, and between 6 and 10m in length. It most likely consists of a single basement level, rectangular window openings with an opening ratio of 0.3 - 0.4, and no architectural detailing.

5 CONCLUSIONS

This study has generated a building typology for a prestigious area of Dublin's City Centre for which the first portion of an underground railway system has been planned. The majority of structures are terraced masonry dating from Dublin's Georgian period (1720-1840), as well as buildings from later in the C19th. Four-storey slender structures predominate, many with a single basement level. Architectural detailing is shown to be limited to the minority of the buildings, even though almost half are protected structures. In the past, the majority of these buildings formed the bulk of Dublin's domestic architecture. However, today 90% have commercial usage.

Specifically relating to the proposed tunnelled project for this region, almost equal proportions are situated parallel and perpendicular to the direction of the tunnel's axis. Furthermore, over half the study area is situated beyond the influence of the resulting settlement trough. Meanwhile, for those within this region the hogging mode of building deformation is shown to be predominant.

This study provides a solid basis for risk assessment of a large number of buildings to be subjected to major infrastructure works. This process forms an important part of urban projects of this nature, as it contributes to the prevention of damage being caused to national heritage, as well as ensuring costs due to damage payouts are minimized.

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