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Evaluation of risk assessment procedures for buildings adjacent to tunnelling works

Julie A. Clarke, Debra F. Laefer *

School of Civil, Structural and Environmental Engineering, University College Dublin, Belfield, Dublin 4, Ireland

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ABSTRACT

Risk assessment procedures for underground projects form a key component of pre-construction efforts since resulting ground movements may cause damage to adjacent structures. Particularly for urban tunnelling works, surface settlements may impinge on a vast number of structures and can result in significant lawsuits unless the appropriate building protection measures are implemented. Although the understanding of tunnelling induced building damage has advanced greatly in recent decades, damage and litigation persist. Hence, this paper reconsiders the pre-construction risk assessment procedures undertaken during the generation of an Environmental Impact Statement (EIS) by formally including considerations relating to a building's historical significance, present usage, and current physical condition. In doing so, a holistic approach to risk assessment is proposed, allowing for project resources to be targeted towards buildings that are most at risk. This is demonstrated through a Class A prediction for a section of an upcoming underground railway system in which 14% of the selected study area of 220 buildings are identified to be at risk. Results are compared to those produced by the official EIS where building vulnerabilities are considered in isolation from the damage prediction assessment and just 5% of buildings are considered to be at risk. The proposed methodology offers a standardised procedure for incorporating both cultural and physical aspects of each building, thereby providing a more systematic, comprehensive procedure for pre-construction risk assessment than previously available.

1. Introduction

Tunnel excavation through soft soils can generate surface settlements that may damage adjacent structures unless accurate risk analyses are conducted and appropriate protection measures are implemented. This is a major concern in urban environments where hundreds, if not thousands, of buildings may be located along the proposed route of a bored tunnel. In recent decades, urban tunnelling projects have increased substantially as a result of rising populations, space restrictions, and growing environmental concerns. This expansion in subsurface construction in urban environments has been accompanied by a corresponding increase in related emergency events (Table A1), such as the 2009 Cologne, Germany collapse, which led to the loss of thousands of historical documents (Curry, 2009).

Catastrophic events such as these, as well as less newsworthy, low-level damage to buildings can result in enormous payouts to third parties. For example, Ireland's recent Dublin Port Tunnel resulted in 334 uncontested building damage claims (approximately 1 in every 8 buildings along the tunnel route), adding approximately €3.5 million to the project cost (Brennan, 2007). Conversely, preventative measures may form a disproportionate percentage of the overall budget. For example, the Crossrail Project (currently under construction in central London) conducted detailed evaluations for 428 buildings along the route, specifying protection measures for 89 buildings (Torp-Peterson and Black, 2001) and resulting in the in United Kingdom's largest instrumentation and monitoring contract to date (ITMSOIL, 2010). Furthermore, the problem extends beyond immediate financial losses. Damage to structures of cultural importance or historic value may also lead to the loss of public support, protests and negative press, thereby threatening the prospects of future projects. For example, on October 1st 2010, more than 50,000 people demonstrated against the Stuttgart 21 project over a wide range of environmental and building protection concerns (BBC News, 2010).

In the European Union (EU), large construction projects, such as a tunnelling scheme, require an evaluation of environmental risk as part of an Environmental Impact Assessment (EIA). Under Article 3 of The European Communities Directive 85/337/EEC (as amended by Directive 97/11/EC), an EIA serves to '*identify, describe and assess in an appropriate manner*…*the direct and indirect effects of a project*…' (EC, 1985). The environmental aspects to be

* Corresponding author. Address: School of Civil, Structural, and Environmental Engineering, Urban Modelling Group, University College Dublin, Newstead, Room G25, Belfield, Dublin 4, Ireland. Tel.: +353 1 716 3226; fax: +353 1 716 3297.

E-mail addresses: julie.clarke.1@ucdconnect.ie (J.A. Clarke), debra.laefer@ucd.ie (D.F. Laefer).

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examined include the following: human beings, fauna and flora, soil, water, air, climate and the landscape (as well as the interaction between these elements), and material assets, including architectural, archaeological, and cultural heritage.

For tunnelling projects, ground movements are a significant threat to cultural heritage, as well as to buildings in poor condition. Presently, there exists a broad range of techniques for predicting tunnelling induced building damage, as will be discussed in detail in Section 2. Furthermore, although not regularly conducted, the North/South Metroline in Amsterdam combined pre-construction damage predictions with real-time monitoring data obtained during tunnel excavation to minimise risk to adjacent structures (Van Hasselt et al., 1999). However, methodologies to date have failed to consider the value attributed to the structure by its community (henceforth referred to as community status) and tend to assume wholly undamaged structures, thereby neglecting a building's current condition.

To consider issues of community status and current condition, this paper examines the efficacy of the EIA in assessing building risk for tunnelling projects. Within this context, the focus is restricted to short-term ground settlements (i.e. those immediately following construction) and does not consider catastrophic failures such as daylighting. A new methodology is proposed that employs quantitative procedures for incorporating a building's community status and current condition.

2. Background

In accordance with the requirements set out by the EU (EC, 1985), the International Association for Impact Assessment defines an EIA as '*the process of identifying, predicting, evaluating and mitigating the biophysical, social and other relevant effects of development prior to major decisions being taken and commitments made*' (IAIA, 1999). The assessment of all identified environmental impacts is commonly provided in the form of a document known as an Environmental Impact Statement (EIS). For tunnelling projects, an EIS includes ground movement predictions resulting from the proposed development and their possible impacts on nearby structures.

The financial ramifications of an accurate EIS cannot be overstated. For example in the year 2001 alone, the insurance sector for tunnelling experienced losses of up to 500% over the paid premiums (Woods, 2002). In response to the situation, the Joint Code of Practice for Risk Management of Tunnelling Works in the UK was produced (ABI and BTS, 2003) and later modified for international usage (ITIG, 2006). This code outlined best practice for risk identification and management during underground construction works. Eskesen et al. (2004) further outlined risk management techniques for use throughout the various phases of a tunnelling project to provide a means for clearly identifying potential problems (e.g. injury to workers, damage to third party property, harm to the environment). This provides a means for selecting and implementing appropriate mitigation measures in a timely fashion. For example, for a project value of approximately 1 billion Euro requiring a construction period of 5–7 years, Eskesen et al. (2004) proposes Table A2 for classifying the consequence class for individual cases of predicted damage or economic loss to third parties.

In general, the impacts of ground movements on adjacent buildings are assessed using a phased approach where an increasing level of detail is applied at each stage, and whereby each stage acts as a filter to reduce the number of buildings to be examined (Burland, 1995; Mair et al., 1996). Early stages generally incorporate conservative empirical approaches based on greenfield scenarios (where the presence of the building is ignored) and their resulting ground settlements, such as the approximated Gaussian profile [as originally proposed by Peck (1969)] to idealise vertical settlements at ground level. This idealisation was later refined by Attewell and Woodman (1982), O'Reilly and New (1982) and Rankin (1988), as well as others (Fig. 1). Damage limits are applied, such as the ground settlement and building slope limits defined by Rankin (1988) where buildings subjected to a vertical settlement of greater than 10 mm and a slope of greater than 1/500 are considered at further, more detailed stages of assessment. These empirical methods rely on the choice of settlement trough parameters, which determine the extent of ground loss and are generally derived from case histories, taking into account the tunnelling method and ground conditions (e.g. Mair et al., 1993).

To estimate building response, analytical methods based on elastic beam theory are generally employed at following assessment stages. These methods apply greenfield ground settlement values onto structures and subsequently employ building damage limits, originating with angular distortion limits (Skempton and MacDonald, 1956) and which was further developed by Polshin and Tokar (1957) by introducing the concept of a structure's critical tensile strain. This concept was later extended by Burland and Wroth (1974), who established the idea of limiting tensile strain. Furthermore, Burland et al. (1977) introduced damage categorisation for buildings in terms of cracking, and later Boscardin and Cording (1989) established a relationship between deflection ratio, horizontal strain, and damage categories.

More recently, numerical modelling has improved damage prediction for structures subject to adjacent tunnelling works through the use of finite element programs. In such work, Potts and Addenbrooke (1997) identified that ground settlement troughs based on greenfield conditions were overly conservative since the building's bending and axial stiffness reduced the trough depth. Franzius (2003) extended this relative stiffness approach by including additional features, such as a building's weight and geometry, as well as the nature of the soil-structure interface. After comparing observed settlements to predicted values, modification factors were developed by Dimmock and Mair (2007) to be applied to greenfield values of deflection ratio and horizontal strain. With growing advancements in computing power, full three-dimensional (3D) analyses are gaining feasibility, from some of the earliest ones by Houlsby et al. (1999), which demonstrated that as a tunnel progresses past a building the nature of cracking changes (i.e. opening and closing).

Despite such advances, claims against tunnelling projects remain commonplace. Arguably, this is exacerbated by a continued focus on idealistic building properties, resulting in: (1) an inability to systematically evaluate the community status of individual structures, and (2) a failure to consistently consider the current physical state of large groups of structures. Moreover, despite recognition by the UK's Engineering Council in their six principles for risk assessment management that the professional engineer should look beyond purely technical considerations and include '*human, organisational and cultural perspectives*' (Engineering Council, 2011), a standardised approach for incorporating the community status of structures as part of risk assessment for subsurface construction has yet to be proposed.

Since the stakeholders associated with a tunnelling scheme may include a broad range of people (i.e. property owners, building tenants, business and professional associations, governmental bodies, the general public), an EIA (and the ensuing EIS) must address their competing interests. Although issues of architectural and cultural heritage are commonly included as part of an EIS, these items are generally considered in isolation from ground settlement predictions. Thus, arguably what is needed is a more integrated approach to risk assessment that combines both physical and cultural aspects of the potentially impacted structures. Introduction of such an approach is proposed herein.