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***Highlights (for review)**

- Holistic approach to building risk assessment for tunnelling works is proposed.
- Both cultural and physical building vulnerability criteria are incorporated.
- Class A prediction presented for Metro North project in Dublin, Ireland.
- Some 14% of buildings are classified at risk levels of 'unacceptable' or 'unwanted'.
- Comparison to the official EIS highlights the need for such an approach.

Evaluation of Risk Assessment Procedures for Buildings Adjacent to Tunnelling Works

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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 if appropriate building protection measures are not 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. 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 appears to be at risk. Results are compared to those produced by the official EIS where just 5% of this area is similarly designated. 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.

Keywords: risk assessment; urban tunnelling; ground movements; historic buildings

1. Introduction

Tunnelling works 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 structures may

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be located along a proposed tunnel route. 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 has been accompanied by a corresponding increase in related emergency events (Table 1), such as the 2009 Cologne, Germany collapse, which led to the loss of thousands of historical documents (Curry, 2009).

Table 1. Soft ground urban environment emergency events (Lance and Anderson, 2006)

Year	Percentage of overall emergency events
1970– 1979	22%
1980 - 1989	32%
1990 - 1999	46%
2000 - 2005	53%

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-Petersen 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 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 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. However, these methodologies fail 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. Eskensen 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, Eskensen et al. (2004) proposes Table 2 for classifying the consequence class for individual cases of predicted damage or economic loss to third parties.

Table 2. Damage or economic loss to third party (Eskesen et al., 2004)

Consequence Classification	Loss (x) in Million Euro
Disastrous	3 < x
Severe	0.3 < x < 3
Serious	0.03 < x < 0.3
Considerable	0.003 < x < 0.03
Insignificant	x < 0.003

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 (Figure 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 10mm 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).

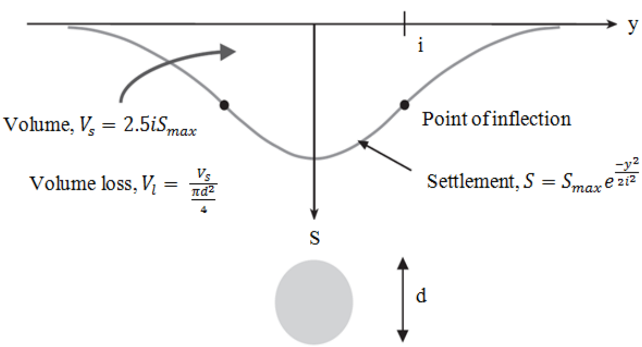


Figure 1. Idealisation of surface settlement trough shortly after tunnelling (after Dimmock and Mair, 2007) where V_s is the settlement volume per unit advance, i is the distance from the centreline to the point of inflection of the curve, S_{max} is the maximum vertical settlement, V_l is the volume loss (ratio of volume of lost ground into the tunnel per unit length with respect to

the theoretical volume of the tunnel per unit length), d is the tunnel diameter, and y is the horizontal distance from the tunnel axis.

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 Skempton and MacDonald's (1956) angular distortion limits and which was 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 (1975), 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 ~~passed~~ 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.

3. Scope and Methodology

The aim of this study is to propose a holistic approach to risk assessment for buildings adjacent to tunnelling works. The proposed methodology will assess individual structures according to both physical and cultural building attributes, offering a standardised approach for the incorporation of these aspects as part of risk assessment procedures. The new methodology will be applied to a section of the proposed route for an upcoming underground railway system in Dublin, Ireland, producing a Type A prediction for this region, as defined by Lambe (1973) but entitled a Class A prediction herein. Findings will be compared to the results of the official EIS produced for Ireland's Railway Procurement Agency as part of the planning process for the project (RPA, 2008).

The study area consists of a region in the city centre of Dublin for which an underground railway system has been granted planning permission (see Figure 2). This area, approximately 1 km^2, forms Dublin’s main retail district along Grafton Street and is a designated Architectural Conservation Area. Furthermore, it is currently nominated for UNESCO World Heritage Status (UNESCO, 2010). This neighbourhood will be subjected to the first phase of tunnelling works as part of the proposed Metro North project. The system will consist of twin bored tunnels, each 6.4m in diameter, to be positioned 15-20m below ground level (RPA, 2008) beginning at St. Stephen’s Green and following the route outlined in Figure 2.

Since risk assessment is described as the process of evaluating both the hazard’s consequence and the probability of occurrence (ABI and BTS, 2003; ITIG, 2006), the procedure proposed herein considers both (see Figure 3). Part A applies traditional methods to determine the degree of damage likely to be incurred. Meanwhile, Part B provides a vulnerability prediction, which relates to the consequences of incurred damage to the individual structure; a concept that has not been incorporated in a standardised manner in the past. This vulnerability prediction quantifies the perceived consequence of damage according to both cultural aspects of the building, as well as its physical condition. Subsequently, a risk assessment is conducted with Parts A and B using a system adapted from Eskesen et al. (2004). The risk assessment is applied to a zone of influence due to tunnelling, dictated by the extent of the predicted settlement trough.

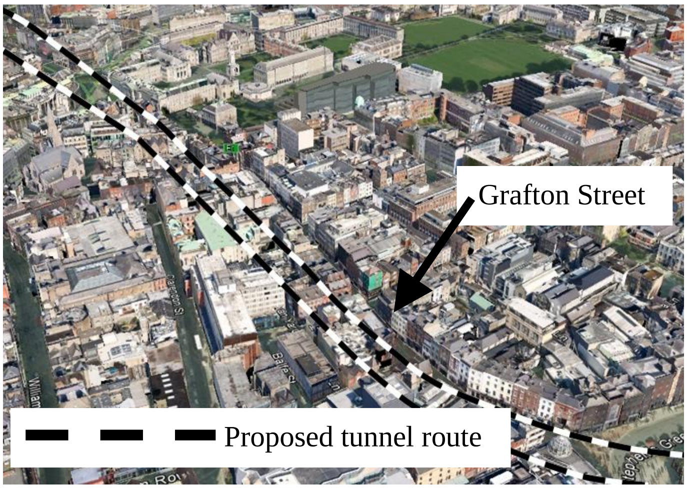


Figure 2. Selected study area - Dublin city centre

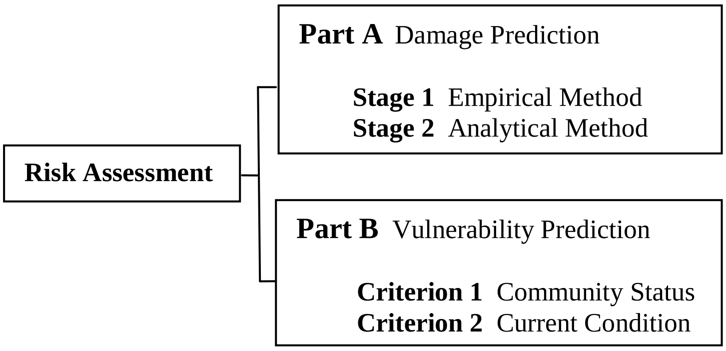


Figure 3. Flowchart outlining methodology

3.1 Part A: Damage prediction

Part A is restricted to two stages. While further stages may offer increased damage prediction accuracy (e.g. numerical modelling), this was considered beyond the scope of the study. Stage 1 consists of traditional empirical limits relating to the maximum vertical settlement (s_{max}) and the maximum slope ($slope_{max}$) of each building within an anticipated soil trough (Figure 4). Since the settlement trough extended to approximately 30m either side of each tunnel axis, these extents were taken to demarcate the zone of influence. Within this region, 220 building addresses were considered herein.

Ground settlements were considered under greenfield conditions where s_{max} and $slope_{max}$ were calculated for each building within the study area. These values were based on formulae proposed by O'Reilly and New (1982) (Equation 1) and Rankin (1988) (Equations 2-4), as well as New and O'Reilly's (1991) relationship to represent the case of twin tunnels (Equation 5), where D is the distance between the tunnel axes, $s_{v\ combined}$ is the vertical settlement resulting from twin tunnels, y is the transverse distance from the tunnel, K is the settlement trough width parameter, and z is the distance from the tunnel axis to the ground level. Equation 5 provides a conservative estimation of the settlement trough generated by twin tunnels since it is based on the superposition of individual settlement troughs. In reality for twin tunnels, one is generally excavated prior to the other. Therefore, ground stiffness is reduced following the construction of the first tunnel resulting in a skewed settlement trough, as revealed by Addenbrooke and Potts (2001).

$$i = Kz \quad (1)$$

$$slope_{max} = s_{v\ combined} / i \quad (2)$$

$$v_s = 2.5is_{max} \quad (3)$$

$$s_{max} = 0.0125V_l\ (r^2/i) \quad (4)$$

$$s_{v\ combined} = (v_s / i\sqrt{2\pi})(e^{-y^2/2i^2} + e^{-(y-D)^2/2i^2}) \quad (5)$$

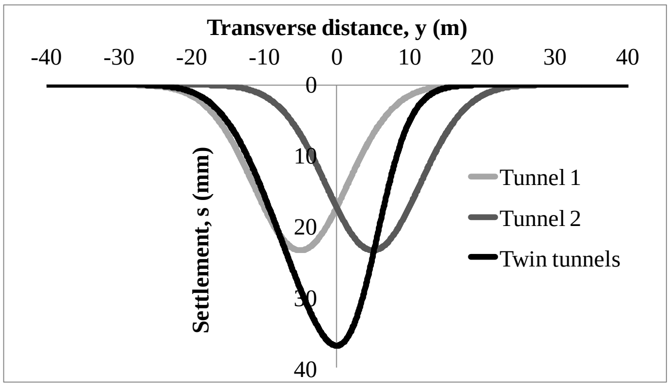


Figure 4. Generated Gaussian settlement trough for twin tunnels

As part of this study, four cases of settlement trough parameters, V_l and K, were examined (as outlined in Table 3) since these parameters can greatly vary depending on site conditions and tunnelling techniques. Case 1 values were adopted previously by Murphy et al. (2010) based on recorded surface settlement values from a nearby tunnel in similar ground conditions. Case 2 parameters were based upon the published EIS (RPA, 2008). Cases 3 and 4 involved a parametric investigation, whereby median values of K and V_l of Cases 1 and 2 were adopted, respectively. Notably, McCabe et al. (2012) considered V_l values of between 0.21% and 1.66% and K values of between 0.47 and 0.55 for nearby areas.

Table 3. Choice of settlement trough parameters

	V_l (%)	K
Case 1 – nearby tunnel	1.18	0.430
Case 2 – published EIS	0.20	0.400
Case 3 – median value K	1.18	0.415
Case 4 – median value V_l	0.69	0.430

Damage categorisation for Stage 1 was determined according to Table 4 where Rankin's (1988) limits provide a preliminary basis for assessment. Therefore, those classified as being of negligible risk were not considered at Stage 2 of the assessment.

Table 4. Typical values of maximum building slope and settlement for damage risk assessment (after Rankin, 1988)

Damage Classification	Max Settlement (mm)	Maximum Slope
High	> 75	> 1/50
Moderate	50 to 75	1/200 to 1/50
Slight	10 to 50	1/500 to 1/200
Negligible	< 10	< 1/500

Stage 2 consisted of an analysis, whereby a damage category was assigned to each building based on the limiting tensile strain concept (Burland and Wroth, 1974; Burland et al. 1977), and the risk chart subsequently developed by Boscardin and Cording (1989) (Table 5).

Table 5. Relationship between damage category and limiting tensile strain (after Boscardin and Cording, 1989)

Damage Classification	Limiting tensile strain (ε_{lim}) (%)
Severe	> 0.3
High	0.15 – 0.3
Moderate	0.075 – 0.15
Slight	0.05 – 0.075
Negligible	0 – 0.05

Burland and Worth (1974) considered the building as a uniform beam with a centrally located neutral axis subjected to a combination of bending and shear (Equations 6 and 7):

$$\Delta/L = (0.167L/H + 0.65\,H/L)\,\varepsilon_{b(max)} \quad (6)$$

$$\Delta/L = (0.25L^2/H^2 + 1)\,\varepsilon_{d\,(max)} \quad (7)$$

where Δ is the difference in deflection between two points, H is the building height, and L is the building length.

These equations enable the maximum extreme fibre strain, $\varepsilon_{b\,(max)}$, and the maximum diagonal strain, $\varepsilon_{d\,(max)}$, to be determined. The minimum of these two values was defined as the limiting tensile strain (Burland, 1995), which was then used in conjunction with Table 5 to assign a damage classification, to each building. For those buildings eliminated at Stage 2, the damage classification of 'negligible' was retained.

3.2 Part B: Vulnerability prediction

Part B consisted of a vulnerability prediction for each structure, evaluating the perceived consequence of incurred building damage. This methodology is similar in nature to the approach now commonly adopted as part of risk analyses within the seismic community where a building's vulnerability is assessed not only according to the expected physical damage but also according to other criteria, such as social aspects and resilience conditions (e.g. Cardona and Hurtado, 2000; Carreno et al., 2007). In this study, the vulnerability of each building was assessed according to two criteria: (1) community status and (2) current condition. The overall classification was determined according to a weighted average that was then normalized by the input components.

3.2.1 Criterion 1: Community status

The community status of each building was evaluated according to its historical significance and current usage, based on the work of Clarke and Hannigan (2009). This evaluation provides a quantifiable means for determining the level to which each individual building is valued by the community (Table 6). For this region, an Architectural Conservation Area (ACA) is defined as an area of special character and architectural interest, while a Conservation Area (CA) is an area which has been recognised for its '*unique contribution and importance to the heritage of the city*' (DCC, 2005). The overall community status score was determined by doubling the score for historical significance and adding the building usage score. Historical significance was weighted higher since this was deemed to result in a more acute measure to gauge community response than building usage. The total score was then normalized by the value 3. The vulnerability classifications are described in terms of the level of project loss, which covers a variety of loss types including financial and public support (see Table 7).

Table 6. Community status scoring system (after Clarke and Hannigan, 2009)

Historical Significance	Score	Current Usage	Score
Protected structure in an Architectural Conservation Area	5	Educational, institutional, community, civic use	5
Protected structure in a Conservation Area	4	Commercial, retail, business use, offices, employment use	4
Protected structure	3	Residential with mixed use commercial, retail, offices	3
Ordinary structure located in a Conservation Area	2	Car parks, areas under construction	2
None	1	Other spaces, recreational uses	1

3.2.2 Criterion 2: Current condition

To determine the current condition of all 220 buildings, each underwent a rapid condition assessment according to the University College Dublin Inspection Method (UCDIM), as proposed by Clarke and Laefer (2012). This enabled the current condition of each building to be determined (see Appendix A). This methodology employs a damage assessment based strictly on the building's façade, since building access for many structures along a proposed tunnel route is often unavailable. A vulnerability classification was determined for each structure according to Table 7.

Table 7. Vulnerability classification levels

Vulnerability Classification	Overall Score for Community Status	Weighted Score for Building Condition	Normalized Score*
Disastrous = Extreme situation where damage may result in excessive project losses	13 – 15	53 – 65	5
Critical = Major losses in case of damage	10 – 12	40 – 52	4
Serious = Substantial losses in case of damage	7 – 9	27 – 39	3
Notable = Some cause for concern due to losses	4 – 6	14 – 26	2
Insignificant = No cause for concern	0 – 3	0 – 13	1

*Community status normalized by 3 and Building condition normalized by 13

3.3 Risk assessment

To provide an overall risk assessment according to Parts A and B for each of the 220 buildings within the zone of influence, Table 8 is proposed. This is adapted from the risk level determination matrix introduced by Eskesen et al. (2004) where descriptions are provided in Table 9.

Table 8. Risk classification (adapted from Eskesen et al., 2004)

Damage Prediction	Vulnerability Prediction				
	Disastrous	Critical	Serious	Notable	Insignificant or N/A
Severe	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unwanted
High	Unacceptable	Unacceptable	Unacceptable	Unwanted	Unwanted
Moderate	Unacceptable	Unacceptable	Unwanted	Unwanted	Unwanted
Slight	Unacceptable	Unwanted	Unwanted	Acceptable	Negligible
Negligible	Unwanted	Acceptable	Acceptable	Negligible	Negligible

Table 9. Risk classification descriptions (Eskesen et al., 2004)

Risk Classification	Actions to be applied
Unacceptable	Risk shall be reduced at least to the “Unwanted” level regardless of the costs
Unwanted	Risk mitigation measures shall be identified. These shall be implemented as long as the costs are not disproportionate with the risk reduction obtained
Acceptable	Shall be managed through the project
Negligible	No further consideration is needed

3.4 Application of methodology

In order to demonstrate the application of the outlined methodology, two building examples according to Case 1 settlement trough parameter selection are provided herein. Example 1 is of 59 Grafton Street (Table 10). For Part A a damage classification of 'slight' (Table 4) was assigned in Stage 1. In Stage 2 it was assigned a damage classification of 'Moderate' (Table 5). For Part B a vulnerability classification of 'disastrous' according to community status was assigned and a classification of 'insignificant' according to its current condition (Tables 6-7). These classifications produced an overall vulnerability classification of 'serious' resulting in a risk classification of 'unwanted' (Table 8). Example 2 is of 54 King Street South (Table 10). For Part A this building was assigned a damage classification of 'slight' (Table 4) was assigned at Stage 1. In Stage 2 it was assigned a damage classification of 'slight' (Table 5). For Part B a vulnerability classification of 'serious' according to community status was assigned and a classification of 'insignificant' according to its current condition (Tables 6-7). These classifications produced an overall vulnerability classification of 'notable', resulting in a risk classification of 'acceptable' (Table 8).

Table 10. Sample Ratings

Example 1	**59 Grafton Street**		**Example 2**	**54 King Street South**	
	Part A Damage Assessment			Part A Damage Assessment	
	Stage 1	Stage 2		Stage 1	Stage 2
	s_v = 31.55mm $slope_{max}$ = 0.005	ε_{lim} = 0.09%		s_v = 36.51mm $slope_{max}$ = 0.006	ε_{lim} = 0.05%
	Part B Vulnerability Assessment			Part B Vulnerability Assessment	
	Criterion 1 Normalised score = 5	Criterion 2 Normalised score = 1		Criterion 1 Normalised score = 3	Criterion 2 Normalised score = 1
'Unwanted'			'Acceptable'		

4. Results

This section analyzes the results of the risk assessment applied to the 220 buildings in the selected study area.

4.1 Risk Assessment for Case 1

Case 1 results are presented in detail in Figure 5 as this offers what is considered to be the best estimate of settlement trough parameters. The damage prediction (Part A) involved two stages. The first was based on greenfield settlement values and damage limits proposed by Rankin (1988) (Table 4). Using these limits, 121 of the 220 buildings exceeded the allowable damage threshold of 'slight'. These buildings were further considered in Stage 2, in which settlement values were imposed using the limiting tensile strain method (Table 5). This more precise method predicted 'moderate' damage for 13 buildings (6% of the study area), 'slight' for 26 buildings (12%), and 'negligible' for the remaining 82 buildings (37%) analysed at this stage.

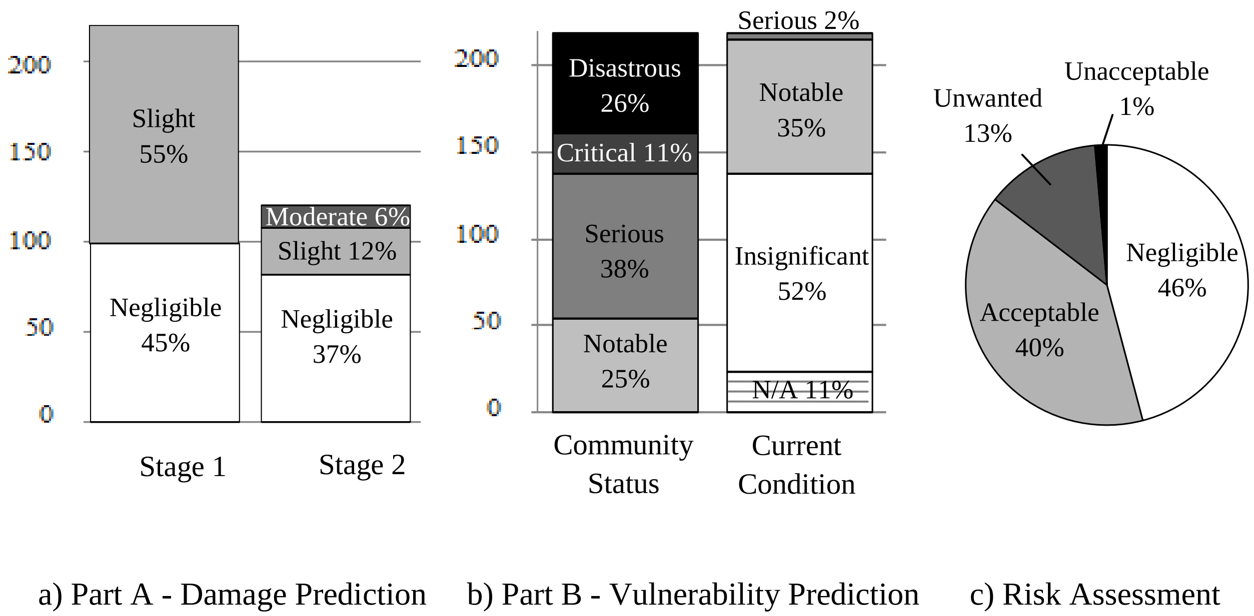


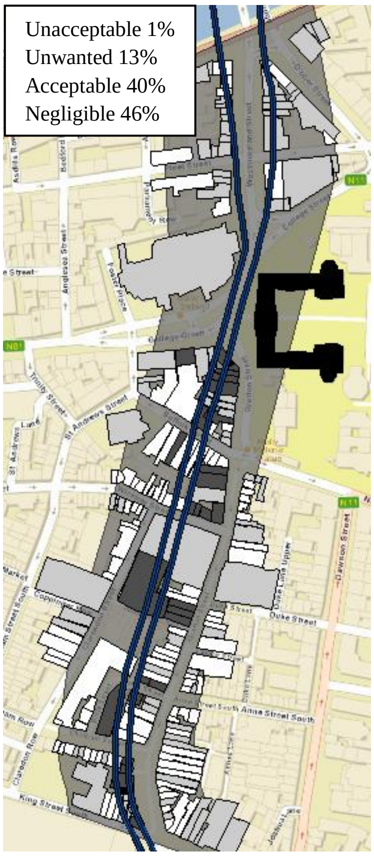
Figure 5. Case 1 Results

The vulnerability prediction (Part B) assessed all buildings according to community status and current condition. Since these criteria are independent of settlement trough parameters, the results are identical for Cases 1-4. According to community status, 58 buildings (26%) were assigned a vulnerability classification of 'disastrous', 24 (11%) as 'critical', and 83 (38%) as 'serious' (as per Table 7). This reflects the large number of highly valued structures in this area. The remaining 55 buildings (25%) was classified as 'notable'. No buildings were classified as 'insignificant' according to community status. According to current condition, no buildings were classified as either 'disastrous' or 'critical', and just 4 buildings (2%) were classified as 'serious'. Another 78 buildings (35%) were classified as 'notable' and 114 (52%) as 'insignificant'. For the remaining 24 (11%) buildings, the method was not applicable, but these buildings were in no apparent physical distress. Using Table 8, a risk classification was assigned to each building: 14% of the study area (or 32 buildings) was classified as either 'unacceptable' or 'unwanted'. Another 40% (or 87 buildings) were at an 'acceptable' risk level, while the remaining 46% were classified as 'negligible'.

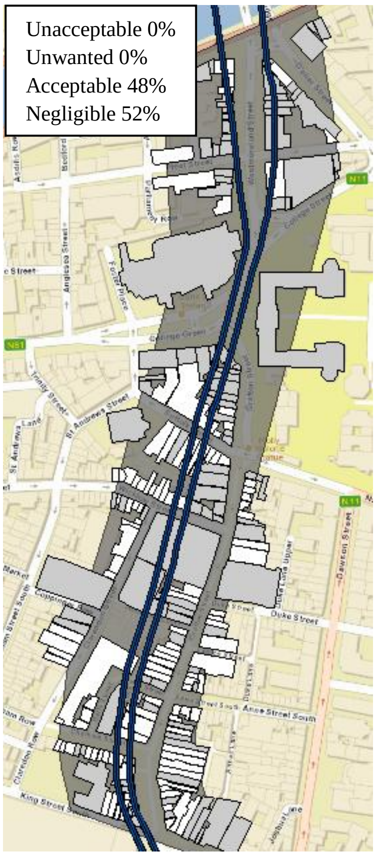
4.2 Influence of Settlement Trough Parameter Selection

The comparative results for Cases 1-4 are presented in Figure 6 where the shaded area denotes the zone of influence. These images depict how the proposed procedure generally identifies the same set of buildings but with different levels of severity based on the choice of settlement trough parameters. Figure 6a illustrates Case 1 where 14% of the buildings are classified as either 'unacceptable' or 'unwanted', as described in the previous section. Case 2 (Figure 6b), which uses the official EIS selected settlement trough parameters, identifies no buildings at a risk level of either 'unacceptable' or 'unwanted'. For Case 3, where a median K value was applied (Figure 6c), 9% of buildings were classified as either 'unacceptable' or 'unwanted'. This shows that a small change in the value of K can affect the severity classifications in the overall risk assessment procedure. For Case 4 where a median value of V_l was applied, just 2% of the study area was classified at a risk level of 'unwanted', directly reflecting the settlement trough parameter choices.

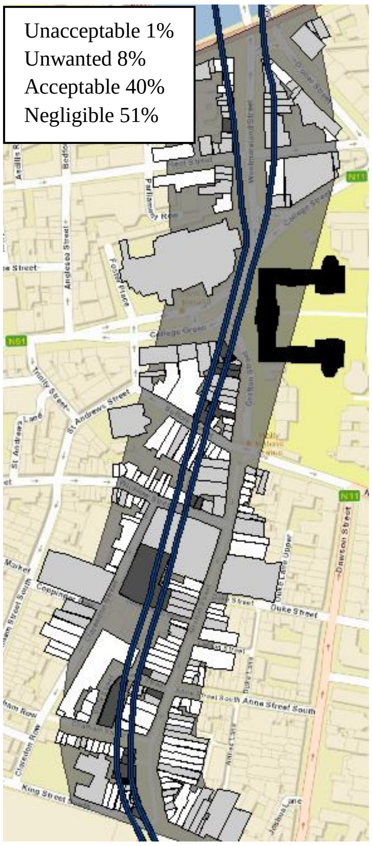
Therefore, the methodology is sensitive to the settlement trough parameter selection, which may be influenced by groundwater conditions, building stiffness, method of tunnelling, and workmanship (Laefer, 2001) but are generally selected based on past projects of similar geology. Since little tunnelling has been conducted in Dublin, the adoption of a conservative approach (i.e. Case 1) would seem appropriate.



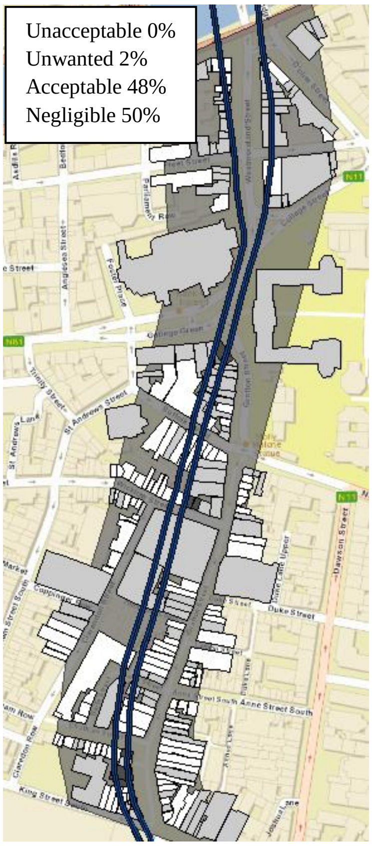
a) Case 1 - Best estimate



b) Case 2 - EIS selection



c) Case 3 - Median value K



d) Case 4 - Median value V_1

Figure 6. Type A prediction for applied study area

5. Discussion

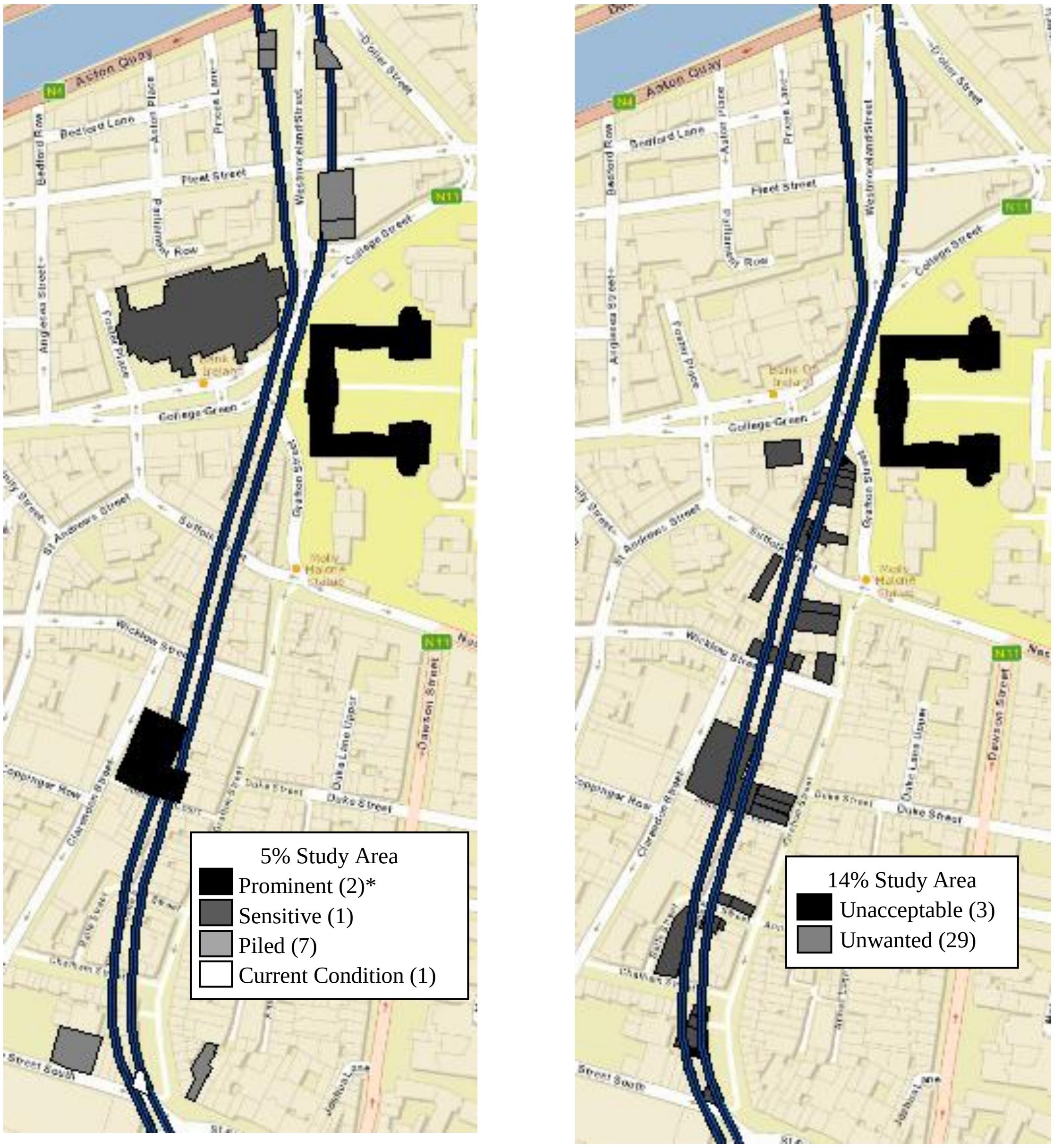
To investigate the efficacy of the proposed methodology, Figure 7 compares the Class A prediction in the form of Case 1 to the official EIS (RPA, 2008). The EIS classified 5% (11 buildings) to be at significant risk. Notably, none were identified in the staged process adopted by the EIS, where Stages 1 and 2 were similar to Part A of the proposed methodology. Instead, the 11 were selected through the application of additional criteria (e.g. a structure's prominence (2), sensitivity (1), foundation type (7), or condition (1)). These buildings were identified by the EIS to be at significant risk irrespective of their status in Stage 1 or 2. Whilst descriptions of 'sensitive' and 'prominent' structures were provided in the EIS, no explicit methodology for building identification was described, nor was a quantification of affiliated risk level included.

Notably, when the EIS settlement trough parameters were applied to the methodology proposed herein (Case 2), no buildings were classified at either the 'unacceptable' or 'unwanted' risk levels, which is identical to the findings of the EIS. Therefore, whilst both approaches recognize the need to assess buildings according to additional criteria, the proposed methodology incorporates these aspects in a formalised and reproducible manner. For the 32 buildings assigned a risk level of either 'unacceptable' or 'unwanted' through application of the proposed methodology, community status was the more onerous building vulnerability criterion for each. The two 'prominent' structures identified by the EIS are included in these 32 buildings and the further 30 identified serve to highlight the need for a standardised approach to the incorporation of such aspects.

The single building highlighted due to its existing condition in the EIS was assigned a vulnerability prediction of 'notable' in the proposed methodology according to the current condition criterion. However, this building was classified at a risk level of 'unwanted' overall due to its community status vulnerability prediction of 'serious'. Although buildings with an existing damage classification of 3 or greater (in accordance with BRE, 1995) were highlighted for further assessment as part of the EIS, assessments do not appear to have been conducted for all buildings within the applied zone of influence, and no further information was provided.

The proposed methodology has the potential to incorporate further building vulnerability criteria, such as building sensitivity and foundation type (e.g. buildings with foundations of at least 4m or 20% of the tunnel axis depth were automatically included in Stage 3 of the UK's

Crossrail Project (CIF, 2008)). In this study area, foundation information was only available for 5.9% of the buildings, thus preventing a systematic incorporation of this criterion.



a) EIS selected buildings for Stage 3 assessment

b) Buildings of equivalent status using the proposed methodology

Figure 7. Comparison of proposed procedure and official EIS

*number of buildings shown in brackets

6. Conclusions

Traditional risk analyses for buildings adjacent to tunnelling works consist of damage predictions that consider an idealised physical problem and do not provide an integrated risk assessment procedure. This study has demonstrated the application of a new methodology that considers both physical and cultural aspects through the incorporation of building vulnerability criteria, consisting of the structure's status within the community and its current physical condition. This methodology offers a holistic approach to risk assessment through the culmination of damage and vulnerability predictions. Application of the proposed methodology has provided a Class A risk assessment for a portion of the Metro North project in Dublin, Ireland, where 14% of buildings are categorized at a risk level of either 'unacceptable' or 'unwanted'. The effectiveness of the methodology is illustrated through a comparison with the official EIS produced for this region where just 5% of buildings are identified to be at risk due to a variety of concerns but through no formalised procedure for considering such aspects. For the 32 buildings identified to be at 'unwanted' or 'unacceptable' risk levels through the proposed methodology, community status was the most onerous building vulnerability criteria for each and these included the two 'prominent' structures detected by the EIS as well as a further single building due to its condition. This comparison emphasizes the importance of adopting a standardised methodology for the incorporation of building vulnerability aspects for pre-tunnelling risk assessments.

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7. References

Addenbrooke, T. I., Potts, D. M., 2001. Twin tunnel interaction - surface and subsurface effects. International Journal of Geomechanics, 2001 (1), 249-271.

Association of British Insurers and British Tunnelling Society (ABI and BTS), 2003. The Code of Risk Management of Tunnel Works in the UK. BTS, London.

Attewell. P. B., Woodman, J. P., 1982. Predicting the dynamics of ground settlement and its derivatives caused by tunnelling in soil. Ground Engineering, November, 13-16.

BBC News, 2010. Germans mobilise against Stuttgart rail project. Available at: www.bbc.co.uk/news/world-europe-11465890 (accessed October 2012).

Boscardin, M. D., Cording, E. J., 1989. Building response to excavation induced settlement. Journal of Geotechnical Engineering, 115 (1), 1-21.

Brennan, M., 2007. The Irish Independent 'Many still awaiting tunnel claim payouts.' Available at: www.independent.ie/national-news/many-still-awaiting-tunnel-claim-payouts-1214977.html (accessed October 2012).

Building Research Establishment (BRE), 1995. Digest 251: Assessment of damage in low-rise buildings with particular reference to progressive foundation movement, pp. 8.

Burland, J. B., 1995. Assessment of damage to buildings due to tunnelling and excavation. Invited Special Lecture to IS-Tokyo 1995: Proceedings of 1st International Conference on Earthquake and Geotechnical Engineering, Tokyo, 1198-1201.

Burland, J. B., Broms, B., DeMello, V. F. B., 1977. Behaviour of foundations and structures: state of the art report. Proceedings of 9th International Conference on Soil Mechanic and Foundation Engineering, Vol. 3, Balkema, Rotterdam, 495-546.

Burland, J. B., Wroth, C. P., 1974. Settlement of buildings and associated damage. Proceedings of Conference on Settlement of Structures, Cambridge, 611-654.

Cardona, O. D. and Hurtado, J. E., 2000. Holistic seismic risk estimation of a metropolitan center. Proceedings of 12th World Conference of Earthquake Engineering, Auckland, New Zealand. Available at: http://www.iitk.ac.in/nicee/wcee (accessed October 2012).

Carreno, M. Cardona, O. D., Barbat, A. H., 2007. Urban seismic risk evaluation: a holistic approach. Natural Hazards, 40, 137-172.

Clarke, J., Hannigan, L., 2009. A three-stage assessment process to predict risk levels due to subsurface construction. Proceedings of 34th Annual Conference on Deep Foundations, Kansas City, Publication no. 89 (AM-2009).

Clarke, J., Laefer, D. F., 2012. A systematic approach for large-scale, rapid, dilapidation surveys of historic, masonry buildings. Journal of Architectural Heritage. DOI: 10.1080/15583058.2012.692849.

Crossrail Information Paper (CIF), 2008. D12 - Ground Settlement. pp. 22. Available at: www.crossrail.co.uk (accessed October 2012).

Curry, A. 2009. Archive collapse disaster for historians. Spiegel Online International. Available at: www.spiegel.de/international/germany/0,1518,611311,00.html (accessed October 2012).

Dimmock, P. S., Mair, R. J. 2007. Effect of building stiffness on tunnelling-induced ground movement. Tunnelling and Underground Space Technology, 23, 438-450.

Dublin City Council (DCC), 2005. Dublin City Development Plan 2005-2011.

Engineering Council, 2011. Guidance on risk for the engineering profession. Engineering Council, London. Available at: www.engc.org.uk/risk (accessed October 2012).

Eskesen, S. D., Tengbor, P, Kampmann, J, Veicherts, T. H., 2004. Guidelines for tunnelling risk management: International Tunnelling Association, working group no. 2. Tunnelling and Underground Space Technology, 19, 217-237.

European Commission (EC), 1985. The European Communities Directive 85/337/EEC. Available at: ec.europa.eu/environment/eia/home.htm (accessed October 2012).

Franzius, J. N., 2003. Behaviour of buildings due to tunnel induced subsidence. PhD Thesis, Imperial College London, UK, pp. 358.

Houlsby, G. T., Burd, H. J, Augarde, C. E., 1999. Analysis of tunnel-induced settlement damage to surface structures. Geotechnical Engineering for Transportation Infrastructure, Proceedings of 12th European Conference on Soil Mechanics and Geotechnical Engineering, Amsterdam, 1, 147-152.

International Association for Impact Assessment (IAIA), 1999. Principles of environmental impact assessment best practice. Available at: www.iaia.org (accessed October 2012).

International Tunnelling Insurance Group (ITIG), 2006. A Code of Practice for Risk Management of Tunnel Works. Available at: www.imia.com (Accessed October 2012).

ITMSOIL, 2010. ITMSOIL wins UK's largest ever instrumentation and monitoring contract. Available at: www.itmsoil.com (accessed October 2012).

Laefer, D.F., 2001. Prediction and assessment of ground movement and building damage induced by adjacent excavation. PhD Thesis, University of Illinois at Urbana-Champaign. pp. 803.

Laefer, D. F, Conry, B., Murphy, D., & Ceribasi, S. (2008). A New Multi-parameter Condition Assessment Scale for Tunnel Risk Estimation." Development of Urban Areas and Geotechnical Engineering, St. Petersburg, June 16-19, ISMGGE, Vol. 2, 571-576.

Lambe, T. W., 1973. Predictions in soil engineering. Géotechnique, 23(2), 149-202.

Lance, G. A., Anderson, J. M, 2006. The risk to third parties from bored tunnelling in soft ground. Research report 453, Health and Safety Executive, Norwich.

Mair, R. J., Taylor, R. N., Bracegirdle, A., 1993. Subsurface settlement profiles above tunnels in clays. Géotechnique, 43(2), 315-320.

Mair, R. J., Taylor, R. N., Burland, J. B., 1996. Prediction of ground movements and assessment of risk of building damage. Geotechnical Aspects of Underground Construction in Soft Ground, Balkema, Rotterdam, 712-718.

McCabe, B.A., Orr, T.L.L., Reilly, C.C., Curran, B G., 2012. Settlement trough parameters for tunnels in Irish glacial tills. Tunnelling and Underground Space Technology, 27(1),1-12.

Murphy, J., Gaynor, S. Laefer, D. F., 2010. Predicted tunnel-induced settlement and damage to Findlater's church with respect to freefield and constructed side considerations. Geo-Florida 2010: Advances in Analysis, Modelling, and Design. FL USA, 1690-1699.

New, B. M., O'Reilly, M. P., 1991. Tunnelling induced ground movements; predicting their magnitude and effects. Proceedings of the Institution of Civil Engineers, Geotechnical Engineering, 118 (1), 25-46.

O'Reilly, M. P., New, B. M., 1982. Settlement above tunnels in the United Kingdom - their magnitude and effects. Proceedings of Tunnelling Symposium 1982, 173-181.

Peck, P. B., 1969. Deep excavations and tunnelling in soft ground. Proceedings of 7th International Conf. on Soil Mechanics and Foundation Engineering, Mexico City, 225-290.

Polshin, D. E., Tokar, R. A., 1957. Maximum allowable non-uniform settlement of structures. Fourth International Conf. on Soil Mechanics and Foundation Engineering, 402-405.

Potts, D. M., Addenbrooke, T. I., 1997. A structure's influence on tunnelling-induced ground movements. Proceedings of the Institution of Civil Engineers, Geotechnical Engineering, 125 (2), 109-125.

Rankin, W. J., 1988. Ground movements resulting from urban tunnelling: predictions an effects. Geological Society, London, Engineering Geology Special Pub., 5, 79-92.

Railway Procurement Agency (RPA), 2008. Environmental Impact Statement - Dublin MetroNorth, v.2, Book 7.

Skempton, A. W., MacDonald, D. H., 1956. The allowable settlements of buildings. ICE Proceedings, Engineering Divisions, 5 (6), 727-784.

Torp-Peterson, G. E., Black, M. G., 2001. Geotechnical investigation and assessment of potential building damage arising from ground movements: Crossrail. ICE Proceedings, Transport, 147 (2), 107-119.

United Nations Educational, Scientific and Cultural Organisation (UNESCO), 2010. The Historic City of Dublin. Available at www.unesco.org (accessed October 2012).

Woods, E., 2002. Insuring an industry. Tunnels and Tunnelling International. October 2002.

APPENDIX A

Table A1. Cracking (after Burland et al., 1977)

Risk Category	Degree of Damage	Approximate Crack Width (mm)
0	Negligible	Hairline cracks
1	Very Slight	0.1-1
2	Slight	1-5
3	Moderate	5-15 or a number of cracks greater than 3
4	Severe	15-25 but also depends on number of cracks
5	Very Severe	Greater than 25 but depends on number of cracks

Table A2. Protruding or loose brickwork (after Laefer et al., 2008)

Risk Category	Degree of Damage	Description of Existing Damage

0	Negligible	All bricks in the same plane
1	Very slight	A few bricks (1-3) are noticeably out of plane / Mortar appears to be loose/weak/missing around 1-3 bricks
2	Slight	Overall, more than 5 bricks appear to be slightly out of plane/ Gaps in mortar are more noticeable/Just perceptible difference in line of brick
3	Moderate	Overall up to 10% of bricks are noticeably out of plane; Noticeable slope in masonry; Windows, lintels, doorframes etc. are noticeably tilted
4	Severe	Overall, up to 15% of bricks are missing entirely; Noticeably outward bulge in the wall; Window lintels and doorframes are at an angle greater than 15 degrees
5	Very severe	More than 15% of bricks are missing entirely Sections of the wall are on the verge of collapse Repair work would require majority of wall to be rebuilt

Table A3. Replaced or repaired brickwork (after Laefer et al., 2008)

Risk Category	Degree of Damage	Description of Existing Damage
0	Negligible	None
1	Very slight	Brickwork was replaced as a result of filling a doorway or window.
2	Slight	Replacement Occurred in rarely occurring small clusters (i.e. 2-6) of bricks
3	Moderate	Replacement Occurred in larger clusters (greater than 6)
4	Severe	More than 10% of the wall is comprised of replaced brickwork
5	Very severe	More than 25% of the wall is comprised of replaced brickwork

Table A4. Exposure-based damage (after Laefer et al., 2008)

Risk Category	Degree of Damage	Description of Existing Damage
0	Negligible	None
1	Very slight	Isolated, rarely occurring chipping (i.e. 1-3 bricks)/ Lower perceptible damage of overall wall.
2	Slight	Perceptible overall damage (weathering) of bricks in wall.
3	Moderate	Numerous examples of significant damage i.e. greater than 5%
4	Severe	Noticeable damage to greater than 15%of bricks in wall
5	Very severe	Greater than 25% of bricks are subjected to heavy chipping / spalling. Bricks are heavily eroded due to exposure

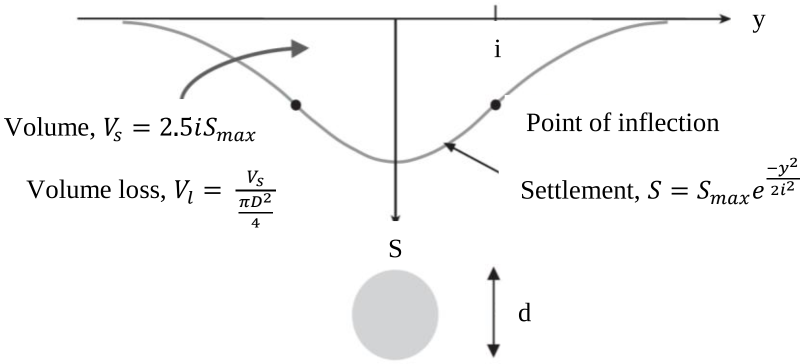
Table A5. Plant growth (after Laefer et al., 2008)

Risk Category	Degree of Damage	Description of Existing Damage
0	Negligible	None
1	Very slight	1 or 2 examples of weeds growing in typical places (i.e. top of chimney, ledge etc)
2	Slight	Weeds are more numerous, as well as being more overgrown
3	Moderate	Whole wall ensconced with vegetation
4	Severe	Minor bush/tree growing out of masonry
5	Very severe	Major (fully mature) tree growing out of masonry

Table A6. Weighting system (after Laefer et al., 2008)

Scale Used	Modifier/Weight Used
Table A2 Crack width	4
Table A3 Protruding/Loose Brickwork	3
Table A4 Damage due to Exposure	3
Table A5 Replaced/Repaired Brickwork	2
Table A6 Plant Growth	1

Figure 1



y
i
Volume, $V_s = 2.5iS_{max}$
Point of inflection
Volume loss, $V_l = \frac{V_s}{\frac{\pi D^2}{4}}$
Settlement, $S = S_{max}e^{\frac{-y^2}{2i^2}}$
S
d

Figure 2

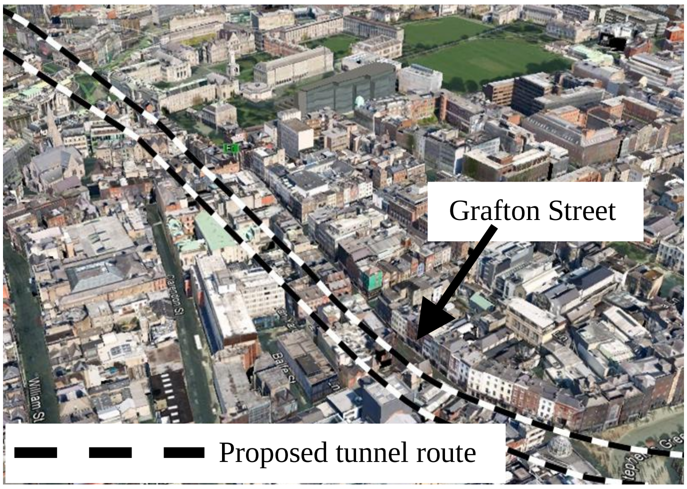
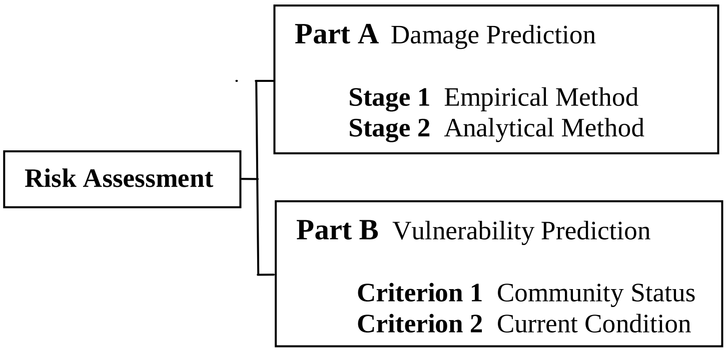


Figure 3



Risk Assessment
Part A Damage Prediction
Stage 1 Empirical Method
Stage 2 Analytical Method
Part B Vulnerability Prediction
Criterion 1 Community Status
Criterion 2 Current Condition

Figure 4

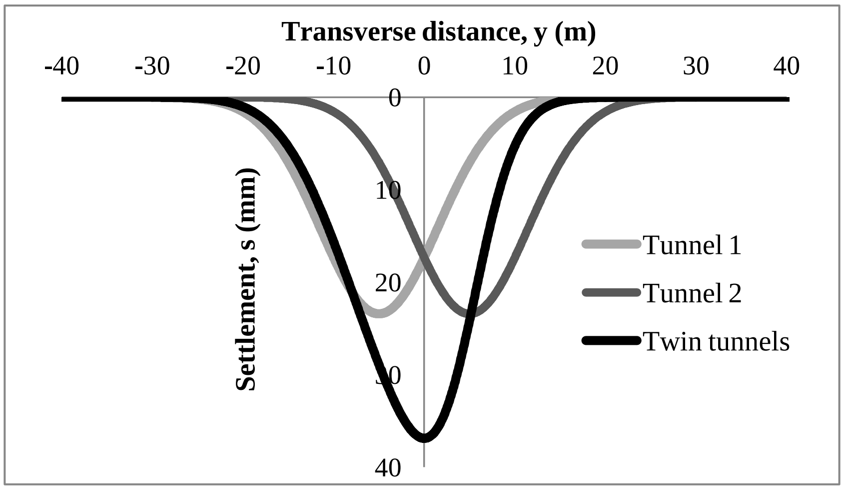

Transverse distance, y (m)
-40
-30
-20
-10
0
10
20
30
40
Settlement, s (mm)
0
10
20
30
40
Tunnel 1
Tunnel 2
Twin tunnels

Figure 5

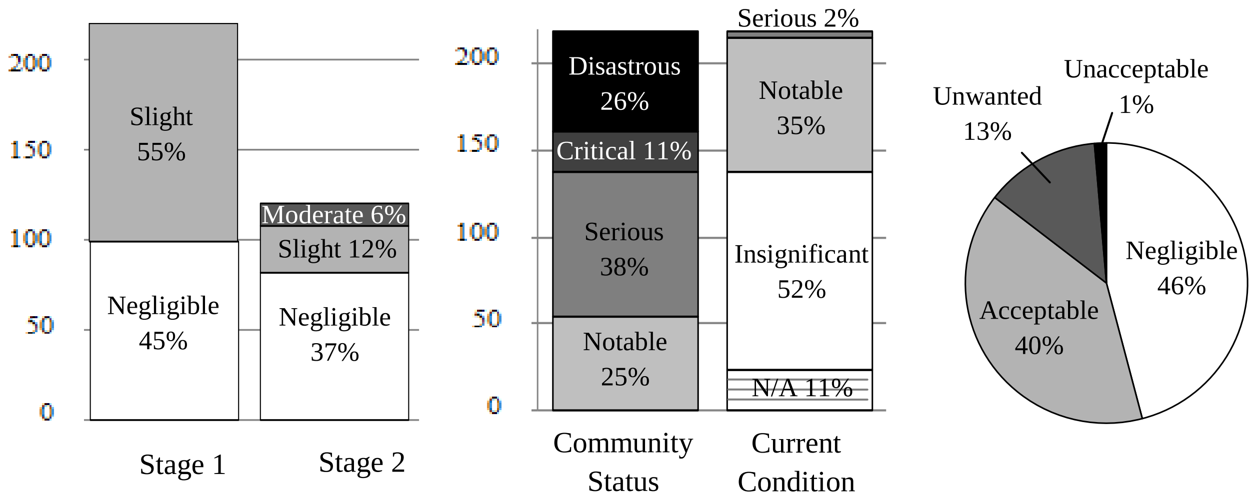

200
150
100
50
0
Slight
55%
Negligible
45%
Moderate 6%
Slight 12%
Negligible
37%
Stage 1
Stage 2
200
150
100
50
0
Disastrous
26%
Critical 11%
Serious
38%
Notable
25%
Serious 2%
Notable
35%
Insignificant
52%
N/A 11%
Community
Status
Current
Condition
Unwanted
13%
Unacceptable
1%
Negligible
46%
Acceptable
40%

Figure 6

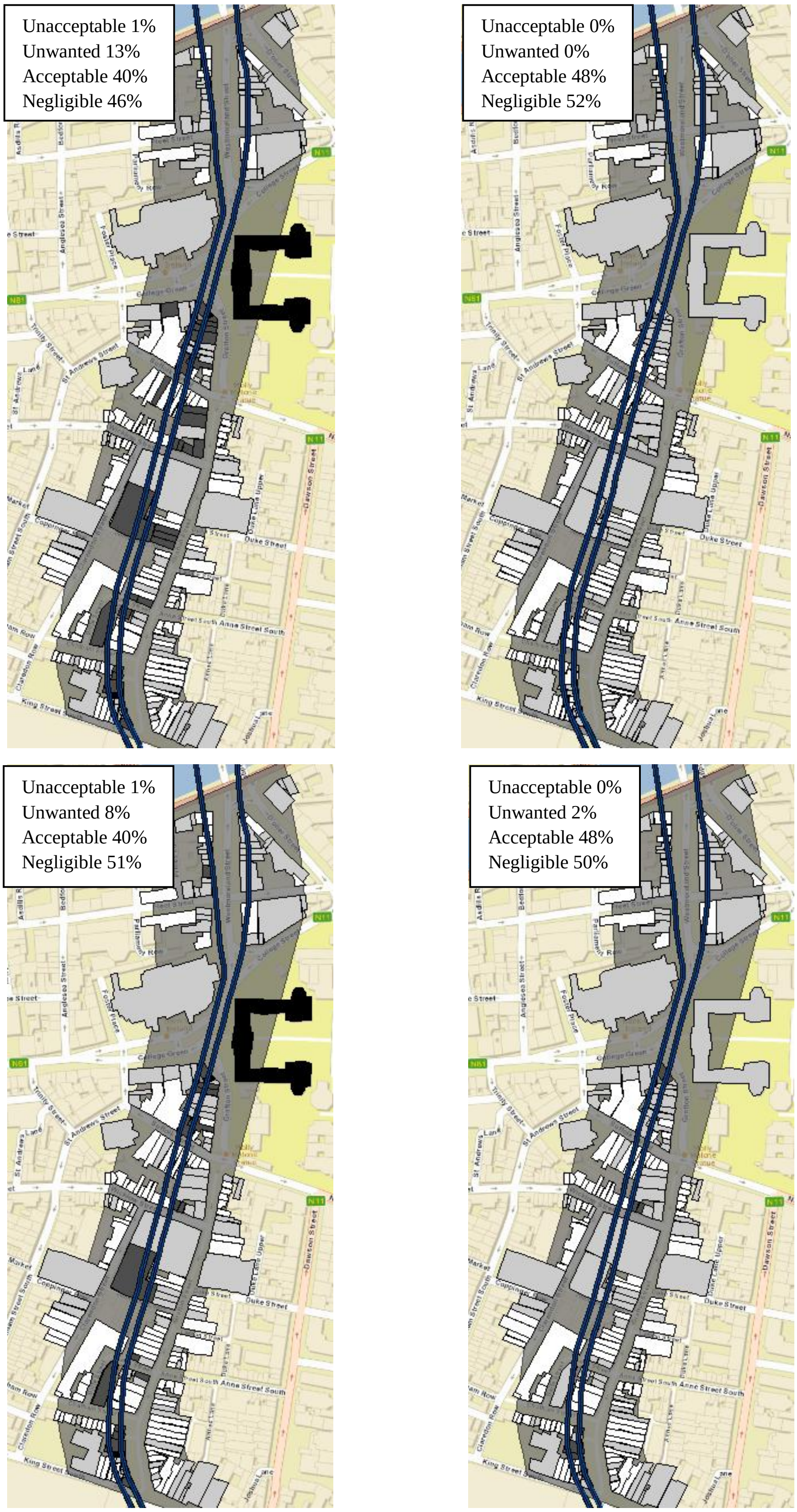

Unacceptable 1%
Unwanted 13%
Acceptable 40%
Negligible 46%
Unacceptable 0%
Unwanted 0%
Acceptable 48%
Negligible 52%
Unacceptable 1%
Unwanted 8%
Acceptable 40%
Negligible 51%
Unacceptable 0%
Unwanted 2%
Acceptable 48%
Negligible 50%

Figure 7


Aston Quay
Bedford Lane
Fleet Street
Westmoreland Street
D'Olier Street
College Street
College Green
Wicklow Street
Dawson Street
Duke Street
5% Study Area
Prominent (2)*
Sensitive (1)
Piled (7)
Current Condition (1)


Aston Quay
Bedford Lane
Fleet Street
Westmoreland Street
D'Olier Street
College Street
College Green
Wicklow Street
Dawson Street
Duke Street
14% Study Area
Unacceptable (3)
Unwanted (29)

Table 1

Year	Percentage of overall emergency events
1970– 1979	22%
1980 - 1989	32%
1990 - 1999	46%
2000 - 2005	53%

Table 2

Consequence Classification	Loss (x) in Million Euro
Disastrous	3 < x
Severe	0.3 < x < 3
Serious	0.03 < x < 0.3
Considerable	0.003 < x < 0.03
Insignificant	x < 0.003

Table 3

	V_l (%)	K
Case 1 – nearby tunnel	1.18	0.430
Case 2 – published EIS	0.20	0.400
Case 3 – median value K	1.18	0.415
Case 4 – median value V_l	0.69	0.430

Table 4

Damage Classification	Max Settlement (mm)	Maximum Slope
High	> 75	> 1/50
Moderate	50 to 75	1/200 to 1/50
Slight	10 to 50	1/500 to 1/200
Negligible	< 10	< 1/500

Table 5

Damage Classification	Limiting tensile strain (ε_{lim}) (%)
Severe	> 0.3
High	0.15 – 0.3
Moderate	0.075 – 0.15
Slight	0.05 – 0.075
Negligible	0 – 0.05

Table 6

Historical Significance	Score	Current Usage	Score
Protected structure in an Architectural Conservation Area	5	Educational, institutional, community, civic use	5
Protected structure in a Conservation Area	4	Commercial, retail, business use, offices, employment use	4
Protected structure	3	Residential with mixed use commercial, retail, offices	3
Ordinary structure located in a Conservation Area	2	Car parks, areas under construction	2
None	1	Other spaces, recreational uses	1

Table 7

Vulnerability Classification	Overall Score for Community Status	Weighted Score for Building Condition	Normalized Score*
Disastrous = Extreme situation where damage may result in excessive project losses	13 – 15	53 – 65	5
Critical = Major losses in case of damage	10 – 12	40 – 52	4
Serious = Substantial losses in case of damage	7 – 9	27 – 39	3
Notable = Some cause for concern due to losses	4 – 6	14 – 26	2
Insignificant = No cause for concern	0 – 3	0 – 13	1

*Community status normalized by 3 and Building condition normalized by 13

Table 8

Damage Prediction	Vulnerability Prediction				
	Disastrous	Critical	Serious	Notable	Insignificant or N/A
Severe	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unwanted
High	Unacceptable	Unacceptable	Unacceptable	Unwanted	Unwanted
Moderate	Unacceptable	Unacceptable	Unwanted	Unwanted	Unwanted
Slight	Unacceptable	Unwanted	Unwanted	Acceptable	Negligible
Negligible	Unwanted	Acceptable	Acceptable	Negligible	Negligible

Table 9

Risk Classification	Actions to be applied
Unacceptable	Risk shall be reduced at least to the “Unwanted” level regardless of the costs
Unwanted	Risk mitigation measures shall be identified. These shall be implemented as long as the costs are not disproportionate with the risk reduction obtained
Acceptable	Shall be managed through the project
Negligible	No further consideration is needed

Table 10

Example 1	59 Grafton Street		Example 2	54 King Street South	
	Part A Damage Assessment			Part A Damage Assessment	
	Stage 1	Stage 2		Stage 1	Stage 2
	s_v = 31.55mm $slope_{max}$ = 0.005	ε_{lim} = 0.09%		s_v = 36.51mm $slope_{max}$ = 0.006	ε_{lim} = 0.05%
	Part B Vulnerability Assessment			Part B Vulnerability Assessment	
	Criterion 1	Criterion 2		Criterion 1	Criterion 2
	Normalised score = 5	Normalised score = 1		Normalised score = 3	Normalised score = 1
'Unwanted'			'Acceptable'		