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Predicted Tunnel-induced Settlement and Damage to Findlater's Church with Respect to Freefield and Constructed Side Considerations

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ABSTRACT

Dublin, Ireland is scheduled to constructing its first metro in 2010, with a pair of tunnels connecting the city center to the airport. This study presents first-order predictions of the anticipated soil settlement and related building damage for a single structure on the route. The structure is a 19th century, stone church on glacial till situated almost directly above the shallowest portion of one of the tunnel crowns and immediately adjacent to a station box. To assess potential damage, a settlement trough is predicted based on another recent Dublin tunnel and the anticipated settlement is applied to the church. Damage predictions based on these freefield predictions are made and then revised as to the anticipated impact of the structure itself based on building stiffness, which significantly reduces the maximum differential settlement from 63mm to 36mm resulting in minimal predicted damage.

INTRODUCTION

The objective of this study was to apply knowledge recently gained from Dublin's only existing tunnel – the Dublin Port Tunnel (DPT) to accurately predict the damage to a prestigious structure along the proposed Metro North Tunnel route. The selected structure is Findlater's church in Parnell Square North at the top of O'Connell Street (Fig. 1). This 19th century, unreinforced, stone masonry church was listed in the project's environmental impact statement (RPA 2008) as one of the most atrisk structures along the tunnel route due to its construction materials, condition, age, and proximity to the proposed Metro North tunnels and attached Parnell Square Station box. Assessment for potential damage was conducted with respect to freefield conditions during the installation of the tunnel and the station. Assessment was repeated giving consideration to ground modification due to the presence of the building.

BACKGROUND

A vital step in assessing the potential impact of tunneling is the prediction of the resulting ground settlements. These may be separated into immediate and long-term settlements. The geotechnical community has long relied upon a Gaussian distribution as seen in eqn. 1, as first proposed by Peck (1969) to establish the shape of the settlement trough over a tunnel as a result of immediate settlement, where s is settlement at a particular point, s_{max} is maximum settlement, y is horizontal distance from tunnel centerline, and i is horizontal distance to the point of inflection.

$$s = s_{max} e^{-y2/2i2} \tag{1}$$

The volume of the surface settlement trough per unit length (Vs) is obtained from integrating eqn.1. The resulting formula is eqn. 2

$$V_s = i * s_{\max} * \sqrt{2\Pi} \tag{2}$$

Predictions of maximum ground displacements are made by substituting expected values of i and V_s into eqn. 2, with V_s calculated from eqn. 3

$$V_L\% = \frac{v_s}{v_o} * 100\% \tag{3}$$

where volume loss (V_L) is empirically estimated, V_o is the original tunnel cross section per unit length, and i a derivative of eqn. 4 by O'Reilly and New (1982)

$$i = kz \tag{4}$$

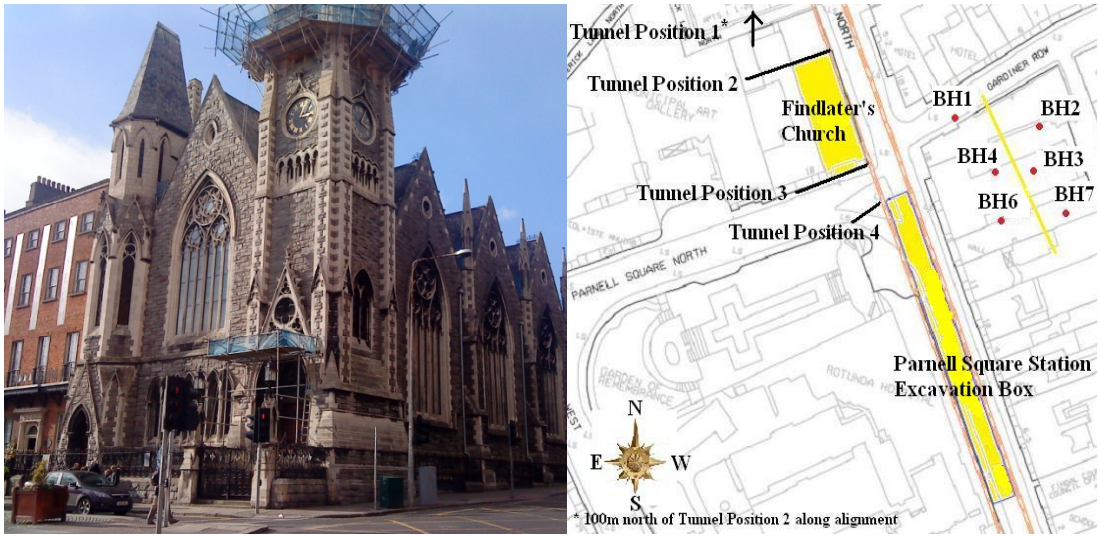
where z is the depth to tunnel crown and k is approximately 0.5 and 0.25 for cohesive and granular soils respectively (O'Reilly and New 1982). O'Reilly and New (1982) used eqn (5) to find the horizontal displacement at distance y, which when differentiated gives the associated strain.

$$h_d = \frac{ys}{z} \tag{5}$$

Strain limits

A shift in thinking in the 1970's changed the focus from freefield settlement predictions to exploring how a building responds under various soil displacement profiles. Burland and Wroth (1974) treated the building facade as simple elastic beam and imposed the freefield settlements on the beam. They showed that critical strain, the strain at the onset of visible cracking could be used to develop a deflection criterion. This was replaced with the limiting strain concept, which allowed for varied serviceability limit states. The limiting strains associated with various crack widths and damage categories are shown in Table 1. Incorporating horizontal strain both diagonal strains induced by shearing and direct strains induced by bending are calculated to find the maximum tensile strain to which the building is subjected. The

limits (Table 1) are then used to classify the damage. Burland (1995) later developed the relationship between deflection ratio, horizontal strain, and damage categories.



(a) Findlater's Church (b) Plan view of church and analysis positions

Figure 1 Church location relative to the tunnels and proposed station box, the recorded borehole data, the cut location and calculated tunnel positions

Table 1 Masonry damage classification (adapted from Burland 1995)

Damage category	Ease of repair	Crack width (mm)	Limiting tensile strain ε_{lim} (%)
0 Negligible	Hairline cracks	< 0.1	< 0.05
1 Very slight	Fine cracks, easily treated during normal decoration.	< 1	0.05 - 0.075
2 Slight	Cracks easily filled. Redecorating probably required	< 5	0.075 - 0.15
3 Moderate	Cracks require some opening up and can be patched by a mason	5 - 15	0.15 - 0.3
4 Severe	Extensive repair work, breaking out & replacing wall sections	15 - 25	> 0.3
5 Very severe	Major repair job, partial or complete rebuilding	Usually > 25	-

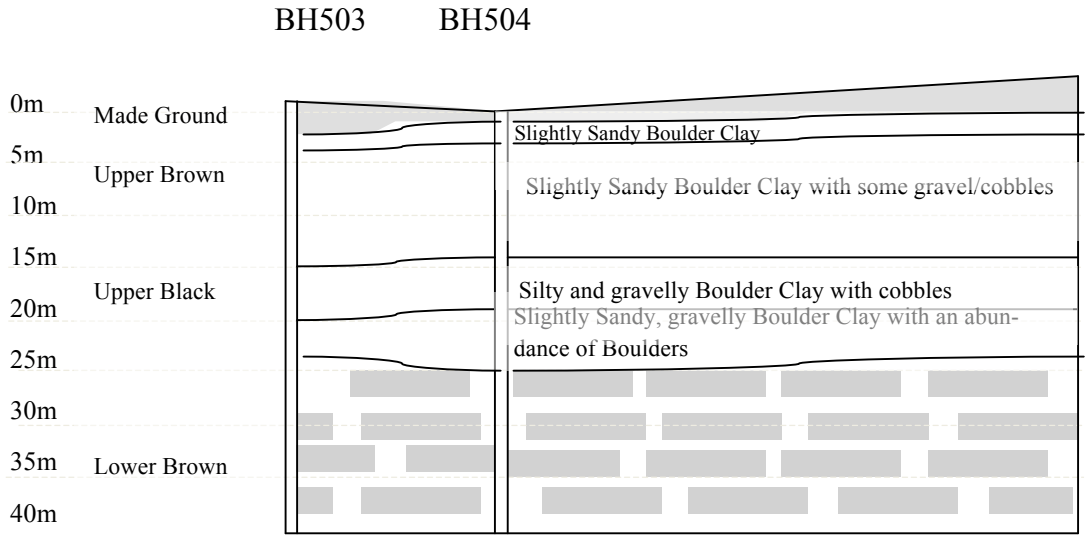
Modification factor charts

Subsequently, Potts and Addenbrooke (1997) conducted a parametric study of the influence of an existing structure on ground movements due to tunneling. This was extended by Franzius et al. (2006) to include three-dimensionality, building weight, soil structure interaction, and additional tunnels. Both studies showed significant differences in settlement profiles compared to freefield cases. The relative axial and bending stiffness values of the beam model became the basis for proposed design charts to modify deflection ratios and horizontal ground strains for the deformation considered (i.e. hogging or sagging). Dimmock and Mair (2008) suggested using only the foundation height in estimation of relative bending stiffness in hogging due to the recorded response of the buildings in their study, as opposed to sagging, where the entire height of the building plus the foundation resist deformation.

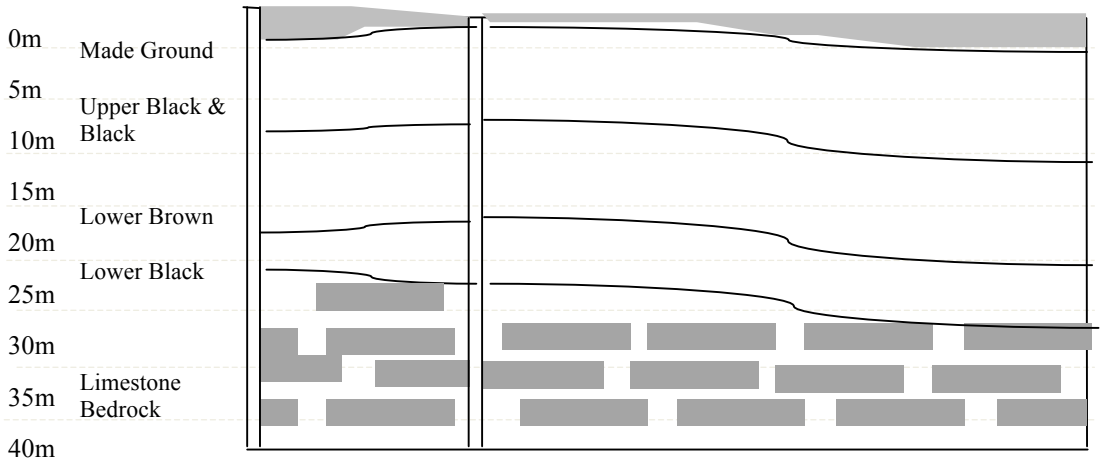
SCOPE

Introduction

Findlater's Church in Parnell Square North at the top of O'Connell Street (Fig. 1) is a 19th century, unreinforced stone masonry church that was listed in the project's environmental impact statement (RPA 2008) as one of the most at risk structures along the tunnel route due to its materials, condition, age, and proximity to the proposed Metro North tunnels and Parnell Square Station box. To best estimate the possible tunnel-induced movements, recorded settlements from the only previous tunneling project in Dublin, the Dublin Port Tunnel (DPT) were investigated to estimate the likely trough shape and magnitude of the Metro North Project tunneling. Both projects involved twin tunnels in similar geology.



(a) DPT – Whitehall borehole



(b) Metro north borehole

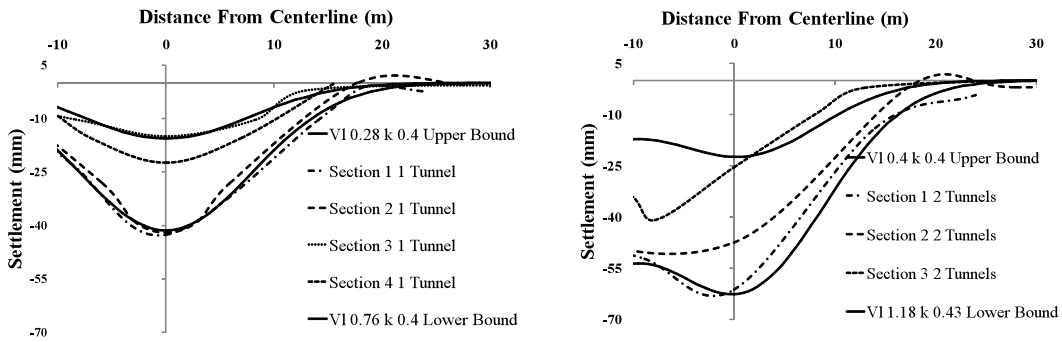
Figure 2. Cross-sections of selected project geologies

Project comparison

Borehole records from both sites were investigated (fig. 2), as well as a recently published study of the DPT (Long and Menkiti 2008). Both sites consist of the layers of Upper and Lower Brown and Black Dublin Boulder Clay (DBC), as reported by Long and Menkiti (2008) and are typical for this region of Dublin. The analysis was, therefore, thought to be readily transferrable from the DPT freefield study site to the Findlater's Church site. Although Metro North is expected to be installed with a tunnel boring machine akin to that used on the DPT, the DPT tunnels are significantly larger (12m versus the 5-7m diameter anticipated Metro tunnels). Thus, use of DPT data for settlement curve prediction may be overly conservative.

Methodology

To estimate the damage, first a settlement trough had to be constructed (fig. 3). To do this, upper and lower bounding Gaussian curves from the Oasys program Tunset (2008) were fitted to both single tunnel pass and double tunnel pass settlement troughs from the DPT site. A range of expected V_L and k values were determined. The most conservative curve parameters were applied to the Tunset model of the expected geometry of the tunnel and station box for the Findlater's Church area. The Burland (1995) damage categories were determined, as well as the differential settlement between the North-West and South-East corners of the Church. Modification to the horizontal strain and deflection ratio according to the Franzius (2006) design charts allowed for the incorporation of the effects of the building stiffness to be considered as part of the damage prediction. The differential settlement was modified using the results from the Potts and Addenbrooke's 1997 study of effects of building stiffness on vertical settlements (Potts and Addenbrooke 1997).



(a) Single tunnel pass troughs (b) Double tunnel pass troughs

Figure 3. Single and double tunnel section troughs

Port tunnel investigation

Construction partners Kellogg, Brown and Root (KBR 2009) provided settlement recordings from the Whitehall area of the Port Tunnel Project, from which four locations were analyzed, and troughs for a single and double tunnel pass were investigated. These troughs provided upper and lower bounding parameters for single and double tunnels in Dublin Boulder Clay (DBC) and provided valuable insights into the probable ground response of the DBC to tunneling elsewhere. The single tunnel measurements were taken in June/July 2003, and the troughs obtained from

the four sections are shown in Figure 3a. The double tunnel analysis occurred in October/November 2003 (Figure 3b). The length of time between passes meant a distinct single tunnel trough was obtained and helped establish that there was approximately a 44% additional maximum soil settlement occurring to the initial settlement trough as a result of the installation of the second tunnel.

The parameters of the upper single tunnel Gaussian curve are V_L=0.28 and k = 0.4. The parameters of the conservative lower single tunnel Gaussian curve are V_L = 0.76 and k = 0.4. The parameters of the upper double tunnel Gaussian curve are V_L = 0.4 and k = 0.4. The parameters of the conservative lower double tunnel Gaussian curve are V_L = 1.18 and k = 0.43.

Freefield building damage

The Tunset program was used to model the Parnell Square Station excavation box and four tunnel locations: three locations as the tunnel drive progresses from the previous stop to the Parnell Square stop and the final layout of the tunnel and excavation box (Figure 1b). Multiple location analysis allowed the worst-case position to be identified. The analyses modeled the excavation box with stiff and soft walls in DBC to fully capture the variable nature of excavation wall stiffness.

As part of the building stiffness calculation the second moment of inertia was calculated as 0.67m^2 in hogging and 341.33m^2 in sagging. To obtain this, only the foundation height was considered in hogging, while the entire building height plus the foundations were included in sagging. This was based on the church having North and South façade lengths of 19m and East and West façade lengths of 44m, with a façade height of 16m and foundations 2m in depth. Furthermore, a Poisson's ratio of 0.25 and a ratio of Young's Modulus (E) over shear modulus (G) 2.6 = E/G was assumed based on previous studies of similar structures (e.g. Burland and Wroth 1974). The building damage results are presented in

Table 2 and illustrated in Figure 4. The results illustrated are for the worst-case façade in each analysis run.

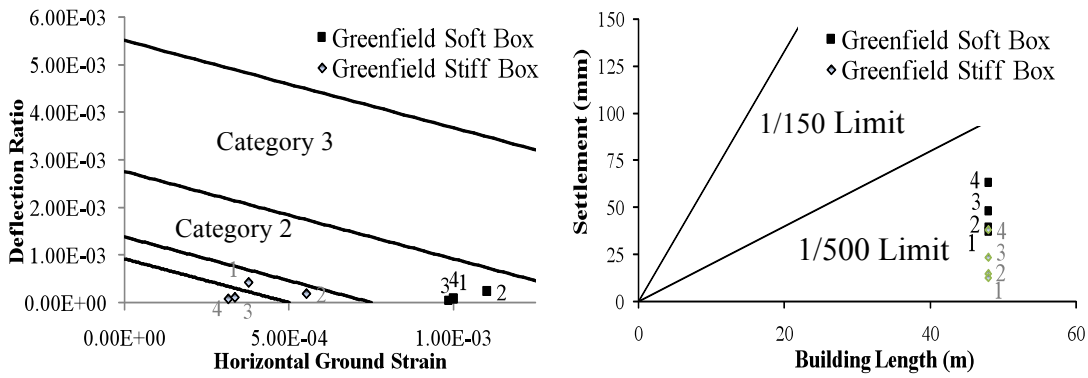
Table 2 Greenfield Stiff and [Soft] Walled Excavation Box Results

		Deflection Mode	Average Horizontal Strain % exp^{-2}	Deflection Ratio % exp^{-2}	Building Side Worst Case	Damage Category	Differential Settlement (mm)
Position	1	Sagging [Hogging]	3.75 [10]	4.36 [0.76]	West & East [West & East]	0,Negligible [2, Slight]	14.83 [39.48]
	2	Hogging [Hogging]	5.52 [11.02]	1.97 [2.38]	East [East]	1,Very Slight [2, Slight]	12.62 [37.26]
	3	Hogging [Hogging]	3.13 [9.83]	0.95 [0.53]	North [West]	1,Very Slight [2, Slight]	23.47 [48.12]
	4	Hogging [Hogging]	3.33 [10.00]	1.23 [0.76]	North [West]	1,Very Slight [2, Slight]	38.39 [63.04]

The worst damage occurs during tunnel construction at tunnel position two, where the tunnel is directly beneath the northern edge of the Church. Damage categories are between 0 and 1 for the stiff walled box and 2 for the soft walled box. The

expected freefield damage is therefore predicted to be category 2 or below, from which Table 1 gives a maximum crack width of 5mm.

The differential settlement figures in Table 2 and Figure 4 show a maximum differential settlement of 39 mm for the stiff-walled analysis and 63 mm for the soft-walled analysis. Both occur at Tunnel Position 4, where the tunnel meets the excavation box. The maximum differential settlement for each analysis run was between the South-East and North-West corners of the Church (Figure 1) due to their positions in relation to the tunnel and excavation box. Terzaghi and Peck (1948) proposed a differential settlement allowable limit of 20 mm and the differential settlement exceeds this significantly in the soft box case. The angular distortion results are all under the Skempton and McDonald (1956) limits for cracking in walls.



(a) Interaction chart after [Burland 1995] (b) Angular distortion limits and results

Figure 4. Building damage and angular distortion for stiff- and soft-walled excavation boxes

Franzius modification

Using charts by Franzius et al. (2006), modification factors for horizontal strain tension and compression ($\varepsilon_{ht}\varepsilon_{hc}$) and deflection ratio in hogging (DR_{hog})and sagging (DR_{sag}) were obtained as 0.1, 0.03, 1.425 and 0.13, respectively. The building bending stiffness only includes the foundation height, while the axial stiffness includes the total façade height. Compression horizontal strain (ε_{hc}) was not implemented, as the worst case is never in compression. The applied charts were designed for modification of beams perpendicular to the tunnel, but Findlater's Church runs nearly parallel to Metro North. Thus, modification was conducted in a similar manner to that adopted by Dimmock and Mair (2008), where modification factors were applied to building lengths for structures also not perpendicular to the tunneling. Using Table 3 and Figure 5, the modified results for the worst-case building damage are shown to be within the Category 0 limit. This is important, as it predicts a significantly reduced damage risk as it classifies the damage as negligible with only hairline cracks. The differential settlement results indicated a greater risk.

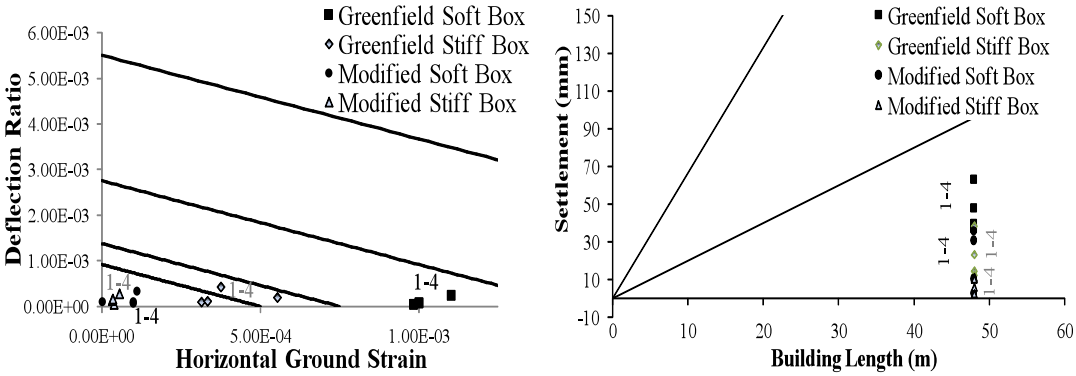
Differential settlement analysis

As found in the results presentation above, the maximum differential settlement for the stiff-walled excavation was 38mm and the soft walled excavation

maximum was 63mm. This is more than the Terzaghi and Peck (1948) advised upper limit of 20mm. The angular distortion was found to result in distortion below the limits of 1/500 (Rankin 1988). However, these results do not take into account the effect of building stiffness on settlement and are arguably, therefore, overestimations. Potts and Addenbrooke (1997) examined the vertical settlement of buildings with different bending and axial stiffness and compared them to the freefield settlements (Figure 6).

Table 3 Building Stiffness Modification Results for Worst Case Façade Using the Stiff and [Soft] Walled Boxes

			Modified as per Franzius				
		Deflection Mode	**Horizontal Strain % (exp^{-2})**	**Deflection Ratio % (exp^{-2})**	**Building Side**	**Modified Damage Category**	**Modified differential settlement (mm)**
Position	**1**	Sagging [Hogging]	0.38 [1.0]	0.57 [1.08]	West & East [West & East]	0, Negligible [0, Negligible]	6.12 [30.90]
	2	Hogging [Hogging]	0.55 [1.10]	2.81 [3.39]	East [East]	0, Negligible [0, Negligible]	11.10 [35.90]
	3	Hogging [Hogging]	0.31 [0.98]	1.35 [0.73]	North [West]	0, Negligible [0, Negligible]	10.39 [35.19]
	4	Hogging [Hogging]	0.33 [1.00]	1.74 [1.08]	North [West]	0, Negligible [0, Negligible]	2.73 [27.52]



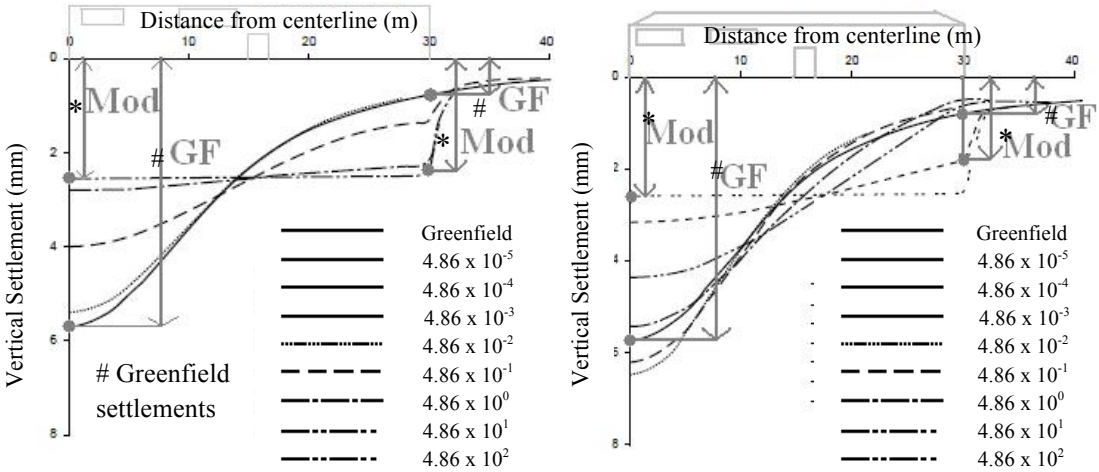
(a) Interaction chart after [after Burland 1995] (b) Angular distortion limits and results

Figure 5. Building damage interaction chart, worst-case results and modified results for stiff and soft walled box

In Figure 6a the bending stiffness values were varied, while the axial stiffness values were held constant. Figure 6b shows the converse. When these parameters were applied to Findlaters Church, the percentage change in settlement from freefield for sagging and hogging was approximately constant for both graphs; with an approximate 225% increase in hogging and 43% decrease in sagging. The percentage change in settlement for the South-East sagging section and North-West hogging section was applied to the results for Findlaters Church, and new differential settlement values were obtained as seen in Table 3.

In the case of the stiff walled box, the worst-case differential settlement was reduced from 38mm to 11mm, which is now within the maximum allowable move-

ment of 20mm recommended by Terzaghi and Peck (1948). In the case of the soft walled box the worst-case differential settlement is reduced from 63mm to 36mm. This still lies outside the upper 20mm guideline, but it is less of a concern than 63mm. This finding might justify an observational approach to the building during tunneling, instead of a more aggressive preconstruction treatment plan, as the box is neither truly "stiff" nor "soft".



*Stiffness included in settlement; #Greenfield settlements

(a) Varied bending stiffness values **(b) Varied axial stiffness values**

Figure 6. Settlement results chart from Potts and Addenbrooke (1997)

CONCLUSIONS

This study predicted the damage to Findlaters Church due to the construction of the Metro North twin tunnels and station box excavation. An emphasis was placed on the calculation of the differential settlement of the Church and a method of modifying this settlement was developed. The 'freefield' empirical method of calculating surface settlement of O'Reilly and New (1982) was employed and the damage to the Church was analyzed according to the Burland (1995) method. The modification method proposed by Potts and Addenbrooke (1997) and amended by Franzius et al. (2006) was performed, and the modified building damage categories were determined. The differential settlement results from the empirical freefield method were modified using charts from Potts and Addenbrooke (1997).

From the Dublin Port Tunnel investigation, it was found that a Gaussian trough with V_L of 0.76 and k of 0.4 was a conservative fit to the measured data for a single tunnel. The effect of the second tunnel was to increase maximum settlement by 44%. The building damage results showed that the damage category depended largely on the type of support of the excavation box and which façade of the building was examined. The worst-case was found to be either the northern or western facades. The results of the modification analysis found that there was a reduction to damage Category 0 (Negligible) for each analysis. The modified differential settlement results averaged a reduction of 41% in the differential settlement compared to the freefield differential settlements. The damage that Findlaters Church may be expected to sustain is categorized as Negligible, with hairline cracks of approximate

crack width less than 0.1mm. It is herein predicted that maximum differential settlement that may be expected is 36mm, despite this being listed in the environmental impact statement as one of the most at risk structures along the tunnel route.

ACKNOWLEDGMENTS

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