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Pioneering Real Time Computational Models for Building Damage Prediction during Adjacent Tunnel Excavation

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Abstract

Numerical modelling is commonly employed prior to tunnel excavation to estimate surface settlements and to predict the response of adjacent structures. Unfortunately, geotechnical and building parameters are difficult to determine for the large geographical extent of a tunnelling project. As such, parametric values for modelling purposes are frequently assumed and are rarely revised to provide updated predictions as field data becomes available. Given advances in 'real time' data availability from subsurface- and surface-based monitoring systems, the question arises of how to better fully exploit this data for improved adjacent building protection. To achieve this, integration of numerical models into the monitoring process to provide updated 'real time' building response predictions is explored. This paper extends existing frameworks which utilize geotechnical field data to provide ‘real time’ predictions to also include building considerations.

Keywords: Surface settlements; building damage; monitoring; real-time data.
1 INTRODUCTION

Computational modelling, particularly finite element modelling, is frequently employed to assess 'at risk' buildings along a tunnel route so as to determine the required building protection measures to prevent settlement induced damage [14]. At present, these analyses are predominantly limited to pre-construction stages where much uncertainty exists as to the exact selection of geotechnical and building parameters. As such, the reliability of these models is currently limited, despite the investment of significant time and resources during project design. Nonetheless, their results dictate the selected mitigation measures to prevent the occurrence of building damage and, additionally, assist in the development of monitoring schemes to determine and control both ground and building movements during tunnel construction, through the application of additional mitigation measures.

Figure 1: Proposed Integrated System

Despite the vast quantities of monitoring readings commonly produced during tunnel excavation, these actual field measurements are rarely exploited to update the design-stage models. As such, numerical modelling has not, to date, been utilized efficiently
for building damage prediction. To overcome these limitations, this paper explores the current role of computational modelling within the framework of tunnelling projects and investigates the possibility of an integrated system (Figure 1), which exploits the monitoring data produced during tunnel construction for 'real time' building damage predictions. To do so, additional steps are required in a timely manner so as to provide updated building response predictions during tunnel excavation. These steps include parameter calibration and subsequent re-analysis of the numerical models.

2 CURRENT PRACTICE

To date, computational modelling for building protection purposes has been predominantly limited to pre-construction predictions of building response to tunnel excavation. Recent advances, specifically in finite element software capabilities, have enabled realistic modelling of soil behaviour [1], the simulation of complex tunnel construction procedures [3], and precise modelling of specific structures [8]. The accuracy of such predictions relies upon the appropriate selection of model input parameters. In general, ground parameters are determined from geotechnical investigation information and from past tunnelling activities in similar ground conditions. However, these parameters can be difficult to determine due to the heterogeneous nature of subsurface conditions and variations in workmanship and management during tunnel construction [12].

More critically, building parameters are frequently shrouded in uncertainty due to an absence of structural drawings and site reconnaissance generally being restricted to non-destructive testing. This is particularly the case for older buildings where structural layouts, foundation details, material strengths, and previous structural movements are often difficult to determine. Consequently, assumptions must be made but are rarely later confirmed in a systematic way by application of actual response data. This failure to verify may be attributed to the current inability to update computational models in 'real time' but is also indicative of the fact that information about the response of an individual building can rarely be extrapolated to predict the behaviour of other structures along the tunnel route. This is due to the variability of a city’s building stock. For example, along the first section of the proposed Metro North route in Dublin, Ireland, wall thickness information was only available for 10.2% of buildings potentially within the tunnel’s zone of influence. Within this sampling, wall thicknesses varied from less than 200mm to values in excess of 400mm [5].
2.1 Monitoring Scheme

Based on computational results, a monitoring scheme is typically implemented within the tunnel’s predicted zone of influence where numerical predictions dictate the types of required monitoring data, as well as the location of measuring points. A scheme will usually consist of instrumentation located in three zones (Figure 2): (1) subsurface monitoring – consisting of in-tunnel geodetic prisms to assess tunnel convergence, as well as borehole instruments, such as rod extensometers and inclinometers, to monitor displacements below ground level; (2) ground surface monitoring – in the form of precise levelling studs to quantify movements at ground level, and (3) building monitoring – comprised of BRE (British Research Establishment) levelling sockets, as well as geodetic prisms that are read by nearby Automated Total Stations (ATS) to track movements in three-dimensional space. The quantity of monitoring instrumentation is largely dictated by a project’s budget, whilst frequency of readings usually depends on (1) instrument accessibility, (2) automated reading viability, and (3) monitoring goals [10]. The results generally include vast quantities of data, particularly for urban projects beneath historically sensitive structures.

Monitoring information is normally reviewed based upon pre-defined trigger levels, which dictate particular actions. Commonly, a system of three or four trigger levels is adopted: green, amber, red, and black [16]. Green and amber triggers generally require data review to determine necessary actions, whilst red and black triggers denote more drastic actions, such as a construction stoppage or tunnel evacuation. Where necessary, intervention measures such as compensation grouting are subsequently applied. The amount, timing, and location of grout injections are determined from monitoring data but are generally limited to the discreet review of individual datasets. However, arguably determination of the actual cause of reaching a trigger level and the likely effect of intervention activities requires an integrated post-processing approach. Such an approach is not currently undertaken which may be largely attributed to the scale of the problem.

2.2 Typical Project

In order to demonstrate the magnitude of a typical urban tunnelling monitoring scheme, an example of a section of an ongoing project in London City Centre is provided herein. The specific sections of this project considered consist of two tunnels in close proximity, over a distance of approximately 0.8km. Within the zone of
influence of these tunnels, there are over 200 buildings for which the monitoring instrumentation outlined in Figure 2 was adopted. The majority of monitoring instruments positioned on building surfaces are read in 'real time'. This makes those readings available immediately after collection [2]. Based upon readings taken every 10 minutes, the monitoring scheme outputs almost 40,000 readings daily. Typically, readings begin 3 months prior to tunnelling activities (to provide baseline readings) and continue during tunnel excavation and then at a reduced frequency following construction, until settlement values are increasing at a rate of less than 2mm per annum. With project completion expected in 2015, over 58 million individual readings are anticipated for only this section of the tunnel.

<table>
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<tr>
<th>Instrument</th>
<th>No. of Instruments</th>
<th>Frequency of Readings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Geodetic Prism</td>
<td>2715</td>
<td>Automated</td>
</tr>
<tr>
<td>2 ATS</td>
<td>100</td>
<td>N/A</td>
</tr>
<tr>
<td>3 BRE Levelling Stud</td>
<td>1120</td>
<td></td>
</tr>
<tr>
<td>4 Precise Levelling Stud</td>
<td>845</td>
<td></td>
</tr>
<tr>
<td>5 Piezometer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Extensometer</td>
<td>145</td>
<td>Manually twice/day</td>
</tr>
<tr>
<td>7 Inclinometer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Geodetic Prism</td>
<td>Varies</td>
<td></td>
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**Figure 2:** Monitoring Scheme during Tunnel Excavation

### 2.3 Impediments

Not only do monitoring schemes consist of an unwieldy dataset that requires substantial processing resources, but the processing power for an average computer does not currently allow for re-analysis of the original models in a timely manner. Arguably for tunnel projects, the full financial benefits are not being obtained from
either existing efforts in numerical modelling or from field monitoring despite significant time and resources invested in these analyses at design stage and furthermore, monitoring schemes frequently costing millions of euro. For buildings in the vicinity of supported excavations, an 'adaptive management approach' has been proposed [6] where monitoring data collection during construction is processed and numerical models are subsequently analysed in real time. However, the proposal of a similar approach for the case of tunnelling, where hundreds of buildings may be present along a route remains a challenge.

3 INTEGRATED SYSTEM

To exploit the vast quantities of monitoring data produced during tunnel construction as a means for updating computational models, a procedure is needed, which calibrates input parameters and subsequently re-analyses the models. Numerical models generally require fundamental ground parameters (e.g. soil friction angle, Poisson's ratio, etc.) and building parameters (e.g. material strengths, soil-structure interface properties, etc.), depending upon the adopted constitutive model. For geotechnical parameters, algorithms may be utilized to perform back analyses using field data to establish in-situ values [13]. These procedures commonly consist of three steps: (1) the error function to assess the difference between the monitored and computed values, (2) the numerical model to simulate the construction process, and (3) the optimization algorithm to reanalyze the numerical model using an iterative process in order to minimise the error function and obtain the in situ parameters. However, these strategies are generally highly complex due to the convergence requirements of the numerical model and, consequently, require significant computing resources. As such, the use of these algorithms in real time is not currently feasible since the timeframe for obtaining updated geotechnical parameters is presently estimated at 8 hours following monitoring data acquisition [6]. For building parameters, the use of similar algorithms for back analysis purposes is possible, but usage in real time is presently not feasible for similar reasons. However, with the likelihood that computer processing power will continue to grow [11], incorporation of these steps as part of an integrated system may be possible in the near future.

Since full-parameter, real-time analysis is not viable, current tunnelling projects utilize simplified methods for updating risk estimations based upon geotechnical field data. For example, the Porto Metro employed the 'Matrix Approach', which used data relating to the tunnel face's geological conditions to
update a risk matrix, initially based upon numerical analyses, which estimated the likelihood of ground surface settlement based upon geological and overburden conditions [9]. To estimate potential damage for individual buildings, settlement predictions were subsequently combined with results of a building vulnerability analysis to produce an overall 'Building Risk Assessment'. However, the numerical model employed for this method based settlement predictions on a 'greenfield' scenario, where simulation of the soil-structure interaction effects was not included. Notably, the consideration of soil-structure interaction effects due to the building’s presence is crucial for the accurate estimation of building damage since the problem is an interactive one. Tunnel-induced surface settlements affect adjacent structures, but the building’s weight, geometry and foundation type influences the development of surface settlements [15,7]. Failure to recognise this interaction can lead to the implementation of unnecessary building protection measures and thus, the occurrence of unwarranted costs.

For the Amsterdam North/South Metroline, an interactive system was utilized which exploited geotechnical field data. Based upon results of an earlier numerical sensitivity study for buildings founded on piles, the surface settlement monitoring information relating to volume loss ($V_l$) values was fed back to inform tunnel boring machine (TBM) operations [18]. Whilst this method included soil-structure interaction effects, it was limited to buildings founded on piles. However, many historic building stocks are founded on shallow foundations (e.g. New York, Dublin). Furthermore, the interactive method did not enable earlier building parameter assumptions to be updated based upon field data relating to building movements. As such, methods to date have been limited to geotechnical considerations. Consequently, the extension of current methods to include building parameter considerations is sought.

### 3.1 Real Time Computational Models

Whilst different buildings may display similar global behaviour to tunnel induced settlements (i.e. tilt/angular distortion), the development of local building damage (i.e. crack formation) may vary significantly depending on individual structures. In fact, relatively small geometrical discrepancies have been revealed to alter local damage predictions in unreinforced masonry buildings, especially for those constructed of weak building materials [17]. As such, the development of an approach based upon the method employed for the Amsterdam North/South Metroline [18], but extended to
account for uncertainty with regard to building considerations, is proposed. To do so, this method proposes the utilization of field data relating to values of building stiffness (E) to provide updated damage predictions, since this parameter has been revealed to play a key role in the response of structures to tunnel induced settlements [15,7]. Building stiffness is composed of axial and bending stiffness components and varies according to building material, structural type, building geometry, as well as pre-existing cracking.

Since building stiffness values may not be determined from field monitoring data solely, as is the case for $V_l$, the following procedure is proposed to provide updated damage predictions for individual buildings (Figure 3): (1) prior to tunnel construction a sensitivity study of values of $V_l$ will be conducted where E is assumed; (2) subsurface monitoring during tunnel excavation will subsequently provide field values of $V_l$, which may be extrapolated with relative reliability over short distances; and (3) subsequently, the applicable model in terms of $V_l$ will be calibrated against field data relating to building movements to provide an updated damage prediction based on actual building stiffness (i.e. building parameter values are varied until the model simulates the building’s field response). The solution will be approximate since the model is purely calibrated against E and not for fundamental building parameters. However, the method offers a reasonable solution which may be obtained using relatively little computational processing power. However, to implement mitigation measures in a timely manner and address the heaving which occurs in some soils ahead of the TBM [12], model calibration must occur ahead of the tunnel face. This calibration should be conducted as soon as any non-temperature related building movement is detected and results may be subsequently linked to grouting activities.
4 CONCLUSIONS

The need for an integrated approach to building damage prediction is vital for the protection of adjacent buildings during tunnel excavation. Whilst future computer processing power may facilitate entire computational re-analyses, which enable the back analysis of fundamental geotechnical and building parameters, these are not currently viable for real time damage predictions. As such, an extension of an existing method that focuses upon geotechnical considerations to include building considerations is proposed. This involves a computational sensitivity study of values of $V_1$ prior to tunnel excavation and the use of these results in conjunction with field monitoring results relating to building movements to calibrate original models for building stiffness values, thus providing more comprehensive, although not exact, real time building damage predictions. This approach offers an intern solution for more economical usage of computational modelling within tunnel projects and better exploitation of monitoring data.
REFERENCES


