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A collaborative research programme on subsidence damage to buildings: Prediction, protection and repair

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ABSTRACT: Predicting how and to what degree buildings of different types will respond to ground movements from underground construction has become increasingly important to the viability of excavations and tunnelling in urban areas. There is also a need to develop effective and economic methods of protecting buildings and services from significant damage. This paper describes a collaborative research project involving the observation of selected buildings affected by the construction of the Jubilee Line Extension in London.

1. INTRODUCTION

Ground subsidence, its interaction with buildings and the associated damage and repair is a major and growing problem. In the U.K. the value of insurance claims due to shrinking and swelling clays alone now amounts to about £500M per annum. The amount of excavation for basements in urban areas is increasing and the construction costs of protecting buildings from excavation-induced ground movements are very large and frequently dictate the excavation and support method. Also there is a significant increase in planned tunnelling for transportation in urban areas and there is growing public awareness and concern over the effects of tunnelling-induced subsidence on buildings and services.

The prediction of ground movements due to clay volume changes, excavation and tunnelling has improved in recent years. However the associated interactions with buildings, and the resulting levels of damage, are not well understood. It is this lack of knowledge which is proving so costly since it is now common for professionals to adopt a very conservative approach both in the design of protective measures and in the repair of subsidence damage. The construction of the Jubilee Line Extension (JLE) has provided a unique opportunity to study the behaviour of buildings and services undergoing subsidence and this paper describes the collaborative research project that has been set up to carry out this work.

2. ASSESSMENT OF RISK OF DAMAGE DUE TO TUNNELLING

Burland (1995) and Mair *et al* (1996) have described the methodology that has been developed for assessing the risk of building damage in connection with the planning, design and construction of recent tunnelling projects - in particular the London Underground Jubilee Line Extension Project. The methodology is based on limited field data and, inevitably, involves some conservative simplifying assumptions.

The methodology involves the following steps:

(i) Calculation of the vertical and horizontal ground movements at foundation level assuming that the building or structure does not influence these (i.e the so called 'green field' site assumption).
(ii) The assessment of maximum tensile strains in the building assuming that it deforms in conformity with the calculated green field site foundation movements (i.e. the stiffness of the building is ignored).
(iii) The maximum tensile strains are related to the potential category of building damage as defined in Building Research Establishment Digest 251.

When such an assessment shows that there is a risk of significant damage, a more detailed assessment is carried out which attempts to take some account of such factors as structural continuity within the building, its relative stiffness in relation to the ground, any previous history of deformation and damage, the sequence of tunnelling and excavation operations etc (Burland 1995). If this detailed assessment still shows a risk of significant damage, consideration is then given as to whether protective measures should be adopted. It is important to appreciate that many factors are not amenable to precise calculation and engineering judgement is required, preferably based on case histories and experience.

There is an urgent need to test many of the assumptions in the above methodology against field measurements of the behaviour of buildings undergoing subsidence. Moreover it is vital that the effectiveness of various protective measures be assessed by means of well documented case records.

3. AREAS OF UNCERTAINTY

The following are some of the major gaps in knowledge in assessing the risk of building damage and the need for protective measures.

3.1 *Subsidence trough*

Reasonably reliable methods exist for predicting the form of the initial surface settlements for single tunnels beneath 'green field' sites. However there are considerable uncertainties as to whether superposition can be used for multiple tunnels and large openings. Moreover there are very few case histories of reliable measurements of horizontal surface displacements and general subsurface displacements. The absolute magnitude of all these displacements depends on the volume loss (the volume of the surface settlement trough per unit length expressed as a percentage of the notional excavated volume of the tunnel). The choice of an appropriate value for design requires experience and is greatly aided by well documented case histories in similar conditions.

3.2 *Time*

There is much uncertainty about the magnitude and distribution of time-dependent movements due to tunnelling and deep excavations. Although this is believed not to be a problem in stiff clays and granular soils, there is a dearth of reliable long-term (up to ten years say) measurements of ground movements above tunnels. Building owners and their insurers are becoming increasingly aware of this gap in knowledge and this issue was raised time and time again during the consultation stage of the Jubilee Line Extension.

3.3 *Ground-structure interaction*

There are few reliable case records of the influence of building stiffness on the shape and magnitude of subsidence-induced ground movements. As a result it is necessary to adopt the very conservative assumption of neglecting building stiffness. This leads to overestimates of building damage, unnecessary concern by building owners and unnecessarily expensive methods of minimising ground movements. Particularly important gaps in knowledge exist on the transmission of horizontal tensile strains into a building and also the response of piled foundations to ground movements - both vertical and horizontal.

3.4 *Damage*

Present methods of damage assessment rely on the work of Burland *et al* (1977) which was originally directed towards construction settlement and not subsidence. Limited progress has been made in addressing the special problems of subsidence and horizontal strains (Boscardin and Cording (1989), Burland (1995)). There is an urgent need for well documented case records in which the onset and progression of damage is traced and related to progressive deformation of the superstructure.

3.5 *Protective measures*

A number of traditional and novel measures are available for minimising the damaging effects of subsidence. Examples of traditional measures include tunnelling techniques designed to reduce volume loss locally, strengthening the ground by means of grout injection, strengthening the structure by ties or props, creating 'fuse points' within a building to localise deformations, structural jacking or underpinning and installing a physical barrier between the tunnel and the building foundation. Recently the use of compensation grouting has been widely advocated as an effective approach. There is very little published information on the effectiveness of the various measures and designers have to depend largely on the experience and expertise of contractors. Well documented case records are urgently required.

3.6 *Remedial measures*

This a controversial area where different specialists may advocate a wide range of remedial procedures for any given circumstance. Advice could range from a small amount of patching and repointing to major underpinning. Once again there are very few well documented case records which can be referred to - particularly on the medium to long-term effectiveness of remedial measures.

4. OPPORTUNITY AFFORDED BY THE JUBILEE LINE EXTENSION PROJECT

Figure 1 shows the route of the Jubilee Line Extension which, together with the geology, is described in detail by Linney and Page (1996). Much of the tunnelling is in London Clay but between Bermondsey and Greenwich it is in the Woolwich and Reading Beds and Thanet Sands.

Between Green Park and Canada Water, over 100 buildings of various types and construction are influenced to a greater or lesser extent by the tunnelling and station excavations. These buildings range from massive monumental masonry structures in Westminster, large hotels, apartments and offices in the Green Park and London Bridge areas to modern brick buildings in Bermondsey and Canada Water. Three tower blocks are within the zone of influence.

The construction of the JLE provides an opportunity for detailed field studies of:

(a) Excavation and tunnel-induced ground movements in various ground conditions.

(b) The performance of a wide range of building types, cladding and finishes when subjected to ground subsidence of varying severity.

(c) The operation and effectiveness of a variety of traditional and novel protective measures.

(d) Various types of repair methods and their effectiveness.

It would not be possible to tackle the problems of building subsidence over such a wide range and in a cost effective manner without tying into a major project of this type. The research team is able to draw on a much wider range of buildings and problems than would be possible with a series of *ad hoc* studies carried out by different researchers over a period of time.

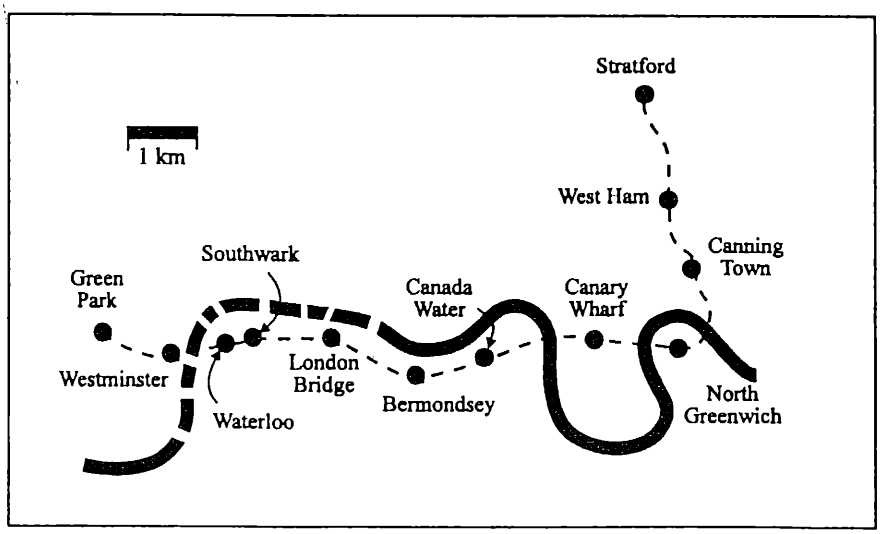

Figure 1 Route of the JLE

In the past it has proved difficult to capitalise fully on the research opportunities offered by large underground construction projects of this type. Although much information is obtained, the day-to-day pressures of the work mean that the measurements are often not gathered systematically and their reliability can vary. Moreover, at the end of the project, the teams are disbanded and records get dispersed and lost. For example, during the planning stages of the JLE, and in particular the Parliamentary enquiry, it often proved impossible to get detailed performance data about previous underground projects.

For these reasons it was appreciated that to derive maximum benefit from the JLE it was important to set up an independent research team to concentrate on measurements and information gathering. A key feature of the Research project is the setting up of a database containing both the research information and the data obtained by the various contractors. The data base will then be available for future projects and for research purposes.

5. THE RESEARCH PROGRAMME

The work comprises four related projects.

5.1 *Ground movements at control sections*

The purpose of this project is to measure surface and subsurface movements remote from buildings at two sites - one in St James's Park, Westminster in London Clay and the other in Southwark Park (Bermondsey) in Woolwich and Reading Beds. Details of the project are given by Standing *et al* (1996). The measurements include precision levelling and horizontal movements of the ground surface, vertical and horizontal ground movements at various depths, pore water pressure measurements and total pressure cell measurements in the vicinity of the tunnels. The instruments and methods of measurement are, in general, significantly more precise than has been used previously for such research (Standing *et al* (1996)). It is intended that the installations should remain in place for a number of years so as to provide reliable information on the important time-dependent effects. The importance of this project is that it provides basic information about the ground movements uninfluenced by soil/structure interaction effects and will prove crucial in improving our understanding of these effects.

5.2 *Building performance*

Eighteen buildings have been selected for detailed study. Selection has aimed to cover a variety of buildings from traditional masonry to framed structures with different claddings. The types of foundation range from shallow strip footings to deep piles. Comprehensive condition surveys have been carried out on the chosen buildings and class A predictions of building response and performance resulting from subsidence have been made on some of them using best current practice.

Measurements consist of precision levelling at ground level and, on some of the buildings, precision taping. It had been originally intended to use high precision photogrammetry for recording the deformations of the superstructure. Experience has shown that greater precision can be obtained using a total station in conjunction with a number of targets mounted on the facade. High quality photographs are being taken to record the development of damage. When cracks are noticed, gauges are mounted across them and their progress is monitored. For a few of the buildings, instrumentation has been placed in the ground beneath the foundations in the form of extensometers and inclinometers in order to study the effects of soil-structure interaction in more detail.

5.3 *Protective measures*

The two types of protective measure that are being most widely used on the JLE are permeation grouting in surface gravels to increase the stiffness of the founding strata and compensation grouting. The effectiveness of both these methods is being assessed by means of the precision surveying described in 5.2 supplemented by contractors' measurements. The work involves close liaison with the JLE staff in the observation and recording of operations, particularly with regard to compensation grouting. The outcome will be a number of well documented case records.

5.4 *Methods of repair*

All the buildings within the zone of influence of the JLE are having precise levels taken on them by LUL. If any building shows signs of damage the research team will, if it is felt to be desirable, be able to undertake additional levelling and instrumentation. Repair work, if required, will be undertaken by the main contractors or by a third party contractor appointed by London Underground Limited. While this work is being carried out it will be observed and recorded by a skilled technician. The effectiveness of the repair will be assessed over as long a period as possible. The objective of this project is to assemble a database of all the repair work that is undertaken.

5.5 *Supplementary work*

In addition to the detailed case histories obtained from the research project, there will be data from a large number of other buildings and structures monitored in less detail as part of the JLE Project works. These data are available to the research team and will be placed on the database and will be used to supplement and support the results obtained from the more detailed studies.

In anticipation of the programme of work described here, LUL have separately sponsored a research project involving numerical analysis of subsidence due to tunnelling and its interaction with buildings. This study is proving of direct benefit to the present research programme in making the class A predictions, in deciding on the most appropriate location of instruments and in the interpretation of the measurements.

6. FUNDING AND MANAGEMENT

Most of the research described in this paper forms a joint industry/ government/ university project within the Government sponsored LINK Programme for Construction Maintenance and Refurbishment (*CMR*) Programme. The Government funding through the LINK CMR Programme amounts to about £380k provided by the Department of the Environment and the Engineering and Physical Sciences Research Council (EPSRC). London Underground Ltd (LUL) and the Geotechnical Consulting Group (GCG) are providing contributions in cash and kind worth about £400k. Further cash funding and in-kind technical contributions are being provided by industry channelled through the Construction Industry Research and Information Association (CIRIA). The work on the control sections described in Section 5.1 is jointly funded by EPSRC and LUL.

Management of the programme is by CIRIA. LUL, through its JLE Project organisation, is providing not only the largest proportion of industrial support, but also the central will permitting it - vital to the success of the research. Imperial College of Science Technology and Medicine is the science-based partner and provides the technical supervision. GCG acts as advisor to the research team.

The research team comprises a senior research fellow, two research assistants and two technicians. At least four undergraduates have worked on the project and a further four academic visitors have contributed in various ways. When extra assistance has been required at critical times most of the research personnel within the Soil Mechanics Section at Imperial College have willingly participated.

The management structure for the research programme consists of:

1. Board of Management to give high level direction and to represent the interests of all the funders.
2. Project Management Committee to support the project manager, to co-ordinate the contributions of participants in the research programme, and to ensure that project targets are achieved.
3. Technical Steering to advise the researchers and vet and approve interim reports.

Monthly progress meetings of the research team are held which include the project manager, the research supervisor, LUL and GCG. These meetings are also minuted and, besides dealing with technical and safety issues, provide a most important means of communication and liaison.

CONCLUSIONS

Prediction of ground movements, the assessment of risk of building damage and the need to provide effective and economic protective measures against such damage are of growing importance in the design and construction of excavations and tunnels in the urban environment. There is an urgent need for fully documented case records on all these topics. The Jubilee Line Extension Project has provided a unique opportunity for establishing a number of such case records. This paper describes a major collaborative programme aimed at making use of this opportunity. It is hoped that the arrangements described in this paper will encourage the development of more collaborative research programmes which take advantage of other major construction projects.

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