Computing power in underground infrastructure design

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Abstract

Recent Underground Rail Infrastructure projects have involved state of the art computer applications used in both the design and construction phases. The availability and low cost of powerful computers has enabled programmes to be developed and used that significantly assist both the design and construction process. The paper will describe experiences that have been gained with these applications on projects such as the Channel tunnel, the London Jubilee Line Extension and the London CrossRail projects. An overview of the benefits of applications including; Finite Element for NATM design, Advanced programmes for settlement production and building damage, and logistics programmes for project management, will be discussed. The use of CAD in these fields will also be addressed. The paper will also look at possible future developments that will enable railways to be constructed in urban areas with improved predictions of their effects on the surrounding environment.

By contrast with the finite element modelling for new projects the paper will finish with a description of the production of a mathematical model for the design of strengthening and refurbishment of a 100 year old rail tunnel. The paper will briefly consider the problems associated with the allocation and assignment of stiffness moduli to naturally occurring materials within a highly complex geology and the calibration of the constructed model to produce believable deflections. The paper will therefore provide a pragmatic perspective of the continuing role of intuition and empiricism in state of the art computer applications.
Introduction

Over the last 5 years powerful PC’s have become available to Engineer’s at comparatively low costs. This availability has led the designers and constructors of infrastructure projects to look at ways in which this computing power can be used to assist in the implementation of these projects and provide economic solutions to traditionally expensive engineering problems. The availability of this computing power has both enabled Engineers to analyse problems in ways that have not previously been practically available to them and has also enabled the cost of analysing many of the traditionally expensive problems to be significantly reduced. In addition to the greater analytical ability and the reduced cost of dealing with problems, powerful available computers have also enabled the time that was necessary for dealing with many of these problems to be significantly reduced.

The impact of this enhanced computing power on the design and construction process will be described with reference to the following examples:

1. Project Management on the Channel Tunnel.
2. Soft Ground Tunnel Design
3. The Design of NATM using Finite Element Analysis
4. Settlement in Urban Areas
5. Computer Aided Draughting
6. Strengthening of a 100 year old Rail Tunnel

1 Project Management on the Channel Tunnel

For the Channel tunnel a combination of a very large computer database and a linked graphics package was used to record, analyse and present the performance data from the TBMs (Tunnel Boring Machines) for use as a live management tool. A TBM drive has the capacity to generate very large amounts of recordable data. In the past either so much data has been collected that analysis becomes impractical, or vital data has been omitted from the records. On this project the computers were used to enable data to be stored, analysed and then presented in a format usable by busy managers. The computer systems developed followed closely the principles of previous manual systems, but the enormous data handling and graphics power of modern computer systems was used to create a highly efficient and effective management tool.

The system that developed on the Channel Tunnel was based on the conventional shift reports that are normally routine on such projects. The only addition to the reporting system was the use of a matrix code chart that
enables what looks like a conventional shift report to be recognised by, entered into and analysed by a computer database. The format of reports was determined by both previous experience and discussions with the management on site, and resulted in a situation whereby the weekly performance of a particular tunnelling machine could be available on a manager’s desk in colour graphical format within 1 hour of the end of a particular week. This live management tool, which could also be interrogated to analyse specific problems, or look at the trend of specific breakdown causes, enabled rapid management decisions to be taken to improve the performance of these TBMs.

On smaller projects it is often possible for the management to have an intimate knowledge of the detailed performance of the equipment under their control. However, on a project such as the Channel Tunnel, with 4000 people working on the site, such intimate knowledge is not possible and therefore management tools such as this are essential if the project it to be managed efficiently. The fact that the tunnelling started badly was bedeviled by problems and was eventually completed three months ahead of the original programme speaks for itself. It is not claimed that this remarkable performance was achieved because of the computer reporting system, but it is obvious that the system was a significant tool that enabled managers to make judgments which eventually led to extremely good tunnelling performance.

2 Soft Ground Tunnel Design

Soft ground tunnel design for circular tunnels and shafts is performed using numerical formulae to calculate forces, moments and deformations in the lining. These formulae are long and awkward to use. Many engineers who have access to PC’s will have used spreadsheet programs or written Basic programs to manipulate these formulae. The use of such verified programs reduces mistakes, improves quality and accuracy, and also reduces analysis and checking time. During the design of Southwark Station for London Underground simple lining analysis and design took about two weeks. This time was reduced to a few days using a computer program for the design of linings for Farringdon Station on CrossRail. The design of non-circular tunnels requires a different approach as there are no published numerical formulae. The simplest approach is to develop beam and spring models (1 dimensional). This method is practically impossible by hand, and five years’ ago would have required expensive large mainframe computers. Today however it is possible to create beam and spring models using most structural analysis finite element packages which include spring supports and beam elements that will operate on any IBM compatible 486 PC with 8Mb or more of RAM. Once the engineer is confident of his model, numerous loading conditions can be quickly analysed using beam and spring models. More sophisticated finite element models in two or three dimensions may also be created which model soil/lining interaction non-linearly and enable the effect of two intersecting or parallel tunnels to be analysed. However, these models can prove expensive to create and analyse, taking several hours to run. The requirements of the design should therefore be carefully
considered before embarking on the use of three dimensional finite element models.

3 The Design of NATM using Finite Element Analysis

Technological improvement in speed and memory capacity of PC’s makes the installation of powerful finite element packages in PC based systems possible. Relatively cheap PC’s and finite element packages justify their application in the design office.

In the past, design of tunnels relied heavily on semi-empirical formulae and rule of thumb. Available formulae are applicable to simple shapes and they are tedious to use.

Finite element methods in tunnelling design offers a greater choice of shape study for a more economic solution. Shapes such as circle, oval, cavern, etc. can be analysed at a comparatively low cost. Behaviour of soil-structure interaction can be better understood.

Currently the NATM design team for Farringdon Station consists of one verification engineer, one modeller and one designer. With the assistance of a PC the amount of analytical work is substantially reduced. To be done without the use of PC’s this work would need a team of 20 engineers and some analyses such as those of non-linear problems may not be possible.

As NATM is a dynamic design process, site monitoring data obtained during construction will be fed back into the models for checking or design refinement. This interactive design approach would be very costly or even not practical without the help of PC’s but is now a relatively economic procedure.

Although finite element packages have been designed to be more user-friendly, this does not imply lower paid and less experienced engineers can be used to undertake computer modelling work. Indeed, computer packages are becoming more and more complicated and the complexity of modelling in some specialised areas may exceed junior engineers’ knowledge.

Powerful PC’s are now relatively economic, resulting in the following advantages of employing a PC in the design office:-

1. Cheap to run.
2. Replaces computer room, leading to saving in office space.
3. Streamlines the size of work force (by a factor of up to 10).
4. Gives better data management in a more organised manner.
5. Provides more alternatives in desk studies and improves our understanding of structural behaviour.
6. Can update data/results quickly with less effort.

All these improve efficiency in production and finally lead to considerable reduction in time and in overhead costs. However, tunnel design is very much a speciality. Members of a design team should be carefully chosen. They should master sound understanding in engineering theories as well as the art of computer modelling. The introduction of Quality Assurance goes some way to help ensuring that these objectives are met.
4 Settlement in Urban Areas

The spatial extent and magnitude of the initial settlement profile caused by tunnelling is reasonably well understood, and can be predicted with confidence for ‘green field’ site conditions. The predictions are based on empirical correlations derived from field observations. In urban areas the presence of building foundations will affect ground movements. However there is insufficient published data to determine the effects of such foundations on the ‘green field’ settlement predictions.

The analysis of the effects on a building of a single tunnel is carried out using a settlement trough calculated using complex sets of formulae that have been derived after years of research. These formulae can be applied to multiple tunnels, but this is where the calculations start to become awkward to handle and lend themselves to computer programs such as SabreTun developed by Babtie Group for use at Farringdon Station on CrossRail.

In modern metro stations there are numerous tunnels, many of which run in parallel, but these are usually linked by cross passages to shafts or escalators. The settlement implications of this complicated layout can only be resolved using a three dimensional analysis. The UK’s Transport Research Laboratory has developed a computer program, TUNSUB to carry out such an analysis. This program can analyse movements and plot contours considering all the tunnels, shafts and diaphragm walls which require to be constructed to form a metro station. It will also carry out phased analysis to enable the effects of different construction programs to be analysed.

These settlement analyses enable the engineer to apply his various settlement reduction techniques, such as compensation grouting, only to the buildings that require it. Indeed, PC based settlement analysis, monitoring of electrolevels and control of grout pumps has enabled the development of automatic compensation grouting techniques, which have been used successfully at Waterloo Station to reduce the effect of a new escalator tunnel on the Victory Arch and BR Waterloo-City Line.

5 Computer Aided Draughting

Powerful PC’s have enabled improvements to be made in CAD drawing production over the last five years. Drawings of great complexity may be produced much quicker than would be possible by hand. Quicker drawing production requires less Technicians and so increases consistency and efficiency. Revisions may be easily carried out to existing drawings. Even major changes may be incorporated without the need for the re-drawing of unaffected adjacent elements, as would be necessary by hand.

Transfer of major project parameters as CAD files for reference by all disciplines reduces the risk of misinterpretation, while producing consistency throughout the project. CAD file transfer also allows plan drawings to be "overlaid" enabling compatibility of work produced by different disciplines to be checked. It is estimated that these developments have doubled productivity in this field.
6 Strengthening of a 100 year old Rail Tunnel

By contrast with the modelling for new projects described above, the following discussion concentrates on the application and production of a mathematical model for the design of strengthening and refurbishment of a 100 year old rail tunnel. The development of the basic model is dependent upon an understanding of the fundamental problem. The interpretation of the problem is described in brief detail, followed by a consideration of the uncertainties associated with the allocation and assignment of stiffness moduli to naturally occurring materials within a highly complex geology and the subsequent calibration of the constructed model to produce "believable" results.

Newton Street Tunnel is a 100 year old brick lined railway tunnel located in Greenock, Scotland. A section of the tunnel passes through a major fault zone and the structural stability of this length of the tunnel has been of concern for a number of years. Continuous monitoring has shown that all previous repairs have been unsuccessful and in particular the records show convergence of the side walls just above cess level. In July 1980 movement of the surrounding mass culminated in a fall of brick from the crown which necessitated emergency repairs and reduced operational capacity from double to single track.

It was apparent that a clear understanding of the complex failure mechanism was required to enable a cost effective design solution to be developed. The initial priority was therefore to determine the basic parameters governing the tunnel behaviour, from which a sophisticated structural analysis could be developed. A review of the historical information revealed that the original brick lining was built on pad foundations and was not intended as a main structural element. At the construction stage the lining was self supporting with occasional locations where the gap between the outside of the lining and the rock face was filled to provide support for a loose area of rock. The geology in the vicinity of the fault zone is complex and the observed problems can be related directly to the geology.

The excavation of the tunnel in the fault zone would have caused considerable loosening to occur in the already weak and highly fractured strata. It is anticipated that this allowed a greater flow of water through the strata and into the tunnel, which in turn caused further loosening of the strata, until individual blocks of tuff became detached and impinged on the lining. The tuff is susceptible to softening and erosion by water so that further deterioration has taken place with time. This has led to the present situation where the tuff surrounding the tunnel has deteriorated in many places to the consistency of a silty clay, with blocks of a stronger, joint-bounded material held in this softer matrix. The areas where distress has occurred are associated with the presence of tuff and water and exacerbated by fracturing of the rock due to faulting. An estimate may be made of the likely loads on the tunnel lining by using Terzaghi’s rock load classification for steel arch supported tunnels. This is appropriate for Newton Street Tunnel, when the method of construction allowed relaxation of the rock mass before the lining was installed.
Using the Terzaghi classification gives loads on the roof ranging from 161 kN/m² to 506 kN/m². It is important to note that in the [Class 6 rock] classification it is remarked that there will be considerable side pressure on the arches. The movements observed are ascribed to a combination of side pressure and softening of the tuff at the base of the arches, reducing the resistance to sliding.

Having gained an understanding of the failure mechanisms and loads acting on the tunnel a mathematical model could then be developed to establish design parameters and predict the likely responses of the structure. Initially a plane frame programme was used to model the arch shape and the programme used in this instance was Stress 3. Using the plane frame analysis the application of the 506 kN/2 m² loading gave reactions and hence pressures under the base of the arch greatly in excess of those which could practically have been sustained. The model also demonstrated that the arch was spreading under load and failure of the arch would occur by the formation of three or more hinges within the structure. The simple remedy was therefore to inhibit this failure mechanism by increasing the effective thickness of the arch and construct an invert slab to restrain inward movements at the base. Building a new inner skin was not possible as the clearance for the trains had to be maintained if electrified double track was to be reinstated. However by grouting the annular space between the brick lining and the rock and also carrying out fissure grouting to a depth of three metres it was considered that the grouted rock would act compositely with the brick lining.

It was not possible using the plane frame model to combine the stiffness of the brick work and the surrounding rock and use this in the plane frame analysis. Hence it was considered more appropriate to develop a finite element model. The choice of stiffness moduli for each material clearly affects the validity of the model. Those used in the finite element analysis were essentially determined from an engineering knowledge of material behaviour combined with previous experience of modelling and of actual brick arch behaviour and modified to produce believable results.

The finite element model was initially used to assess the effect on the arch of grouting the void behind the brickwork. It was assumed that the arch received no support from the previous lifts of grouting and hence there was no requirement to consider the interaction between the arch and the adjacent rock. Having proved that the stresses induced within the arch were acceptable during grouting, the model was used to analyse the performance of the arch in its final state, ie. with the void behind the arch fully grouted, and with the jointed tuff strengthened by means of injection grouting.

The original model comprised: 0.075 m sprayed concrete; 0.7 m brick; 1 m grouted tuff; 2 m jointed tuff; 4 m semi-jointed tuff and finally sound tuff, modelled by spring supports. The initial concept of restraining the edges of the sound tuff by spring supports was found not to be realistic in that any application of load was being restrained by the springs along the top and side boundaries of the model. The extent of the original model was also found to be too large as the stresses induced in the 4 metre layer of semi-jointed tuff were very low. It was therefore necessary to re-adjust the
The sensitivity of the model was assessed by varying firstly the E-value of the grouted and jointed tuff and then varying the E-value assigned to the brickwork. In the first run the strength of the rock was increased from 700 or 800 MN/m² to 2000 MN/m² and, as would be expected, the model predicted a more uniform deformation and stress distribution along the base. In the second run, the brickwork was given a value of 3740 MN/m² compared with the initial value of 8000 MN/m². This had the effect of shedding more load onto the surrounding rock and also onto the sprayed concrete lining. From these sensitivity analyses, the range of stresses predicted in the various elements of the model were then used in the final design.

The development of the finite element model, based on a design concept, involved an iterative process to achieve a realistic representation of the observed and anticipated tunnel behaviour. The parameters governing the sensitivity of the model were investigated and the initial remedial works concept was confirmed as a practical design solution. Consideration was also given to the construction sequence of the remedial works. Controlled lengths of excavation would be required to construct the reinforced concrete invert slab, involving the removal of the consolidated ballast up to a depth of 1.2 m. It was assumed that the ballast was acting to some extent as a strut under the application of external forces to the tunnel lining, and that there would be some form of stress redistribution when the ballast was removed. It was found that the numerical value of the inward deflection of the lining could range from 0.28 mm to 10.1 mm. The most appropriate value was believed to be of the order of 1.0 mm. Actual measurements recorded during the construction of the invert slab have shown total movements of up to 10 mm, with the majority of the recorded movements falling in the range 0 to 8 mm. While it is not possible to tell due to the measurement technique whether these movements are equally shared by each side, the range is nevertheless sensibly within that which was both anticipated and predicted.

7 Conclusions

The contribution which computing power makes to the design of underground infrastructure is immense. It enables the rapid assessment of the effects of varying scenarios on the stresses which have to be catered for. Nevertheless computing power remains a tool which requires to be used in conjunction with pragmatism and considerable judgment.

In the early 80's only large design offices could afford to have their own computer system which could support a limited number of users. The speed of a PC has been greatly enhanced; a 486/66MHz PC can complete a 1000 finite element model analysis within half an hour. For bigger size models, they can be run overnight.

The above examples indicate the "quiet revolution" that powerful PC's have made in Underground Infrastructure Design. As with all such dramatic changes it is difficult to look back and fully comprehend the way in which design was carried out only 10 years ago.