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Geological mapping in urban areas

The BGS experience in London

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The British Geological Survey has established the LOCUS (LONDON Computerised Underground and Surface) geological project, whose aim is to provide geological maps and interpreted data for London. The resultant high-quality model has already proved valuable in projects ranging from the site-specific to strategic overview.

The perceived requirement for geological information in urban areas is to support land-use planning, environmental matters, project planning and civil engineering. With increasing demand for urban geoscience information, the Survey has developed a geologically attributed digital map-production system. This system is structured to provide, on demand, up-to-date colour-printed geological maps at any scale. Thematic maps illustrating specific aspects of geological data are produced also. The output is made available in hard-copy and digital form for GIS applications.

Additionally, a digital relational database has been established using information from 20,000 borehole records for London. Borehole site data and levels, the base of man-made ground and three key geological horizons are used for three-dimensional computer modelling. For London, these horizons are the base of the superficial deposits, which are essentially the sediments deposited by the River Thames; the base of the London Clay, which underlies much of London and is the best tunnelling medium; and the top of the Chalk, an important aquifer in the London Basin. Implementation of digital map production and the rationalisation of, principally, borehole information has enabled routine production of computer-generated geological models of London and provided the means to visualize automatically a range of information from point data to 3-D models.

Introduction

The London region, with a population in excess of 6.3 million, is one of the major conurbations in western Europe. The processes of planning and development in the region, in common with all urban areas, can benefit from a knowledge of the ground conditions which are encompassed in geological information. Such information, when used appropriately, will ultimately result in cost benefits by effec-

tively leading to better interpretation of ground conditions and prediction of potential geological hazards. However, the potential value of sound geological knowledge in underpinning planning and urban regeneration issues has been largely underplayed, and the benefits of detailed understanding of the relevant geological factors, for the most part, have not been fully realised.

Costly remedial work during construction caused by unforeseen geological factors is not uncommon in the London region, and the variability of strata below London has been a source of engineering difficulty dating back to the first tunnel under the Thames, built by Brunel in 1825. Now, after careful study of the geology and the processes that have laid down the different deposits, there are explanations for the formerly "mystifying" changes of rock type beneath London and many of their variations can be predicted.

The statutory framework under which development can take place in Britain puts the onus on local authorities to ensure that a physically safe environment is established, and it is a developer's responsibility to clean up contaminated sites. This means that the planning process must take account of the risks that geological hazards might pose. In the London area these hazards include landslip, dissolution subsidence, chalk-mining subsidence, ground heave, compressible strata, high groundwater and rising groundwater, derelict worked ground, landfill sites and landfill gas, and high-sulphate groundwater. The perceived requirement in rapidly developing and regenerating urban areas, therefore, is for geological information to support land-use planning, environmental matters, project planning and civil engineering. The LOCUS (LONDON Computerised Underground and Surface) geology project was established to meet this requirement. The project is concerned with making new geological maps and computerised geological models of London and the

Figure 1.—London and the surrounding region.

surrounding region (figure 1). This work utilises recent advances made by the British Geological Survey (BGS) in the development of digital borehole databases and digital production of geological maps and draws heavily on the wide range of geological expertise and experience of the Survey staff.

The project was set up with three main aims and objectives:

- to produce geological maps of London at scales of 1:10,000 and 1:50,000
- to establish a digital relational borehole database
- to produce computer-generated geological models of the main subsurface rock units.

Geology of London

The London region lies astride the valley of the River Thames on Cretaceous Chalk and unlithified Palaeogene clays and sands. The overlying superficial deposits principally consist of Quaternary gravels laid down by the Thames.

The Chalk was deposited across the entire region. It was folded and eroded, leaving about 220 m thickness in the London region, prior to deposition of the Palaeogene strata. The Palaeogene sequence, up to 180 m thick, was laid down at the margin of the contemporary North Sea and records a succession of transgressive events caused largely by eustatic sea-level changes. The lowest beds (Thanet Sand Formation and Upnor Formation) are mainly shallow marine sands. They are succeeded by brackish-water sands and lagoonal clays (Woolwich Formation) and alluvial muds that were subjected to pedogenesis (Reading Formation). Another marine transgression led to the deposition of a thick succession of marine muds (London Clay Formation) which grade into shallower-water marine sands (Bagshot Formation). A generalised succession of these beds is shown in figure 2.

The geological structure of the region is relatively simple, being dominated by a broad southwest-to-northeast-trending syncline (the London Basin), flexed during the Alpine orogeny in Miocene time,

with limb dips generally less than 2° . In central and southeast London small periclinal, with axial-plane traces roughly parallel to the main syncline and with limb dips up to 5° , are superimposed on the larger structure. The Chalk crops out around the margins of London, forming the relatively high relief (over 130 m above sea level) of the North Downs and Chiltern Hills, and in the cores of some periclinal, for example Purfleet in the east and Windsor in the west. Palaeogene sediments were folded with the Chalk and form the core of the London Basin (figure 3). Few faults are known, the principal ones being normal, with a curving northeast trend. Minor flexures in structure contours suggest also northwest-trending flexures or faults.

In early to middle Quaternary (Pleistocene) times, a river ancestral to the Thames flowed northeastward to the north of London (Gibbard, 1985). During the Anglian stage, some 350,000 years ago, a major ice sheet advanced southward across Britain as far as the northern part of the London region, leaving a till deposit which has subsequently been dissected. This ice sheet blocked the valley of the ancestral Thames (Gibbard, 1977), diverting the river to its present course. Subsequently, fluvial sands and gravels assigned to seven river terraces have been deposited in the 10-km-wide present valley. They are about 2 to 5 m thick and overlie benches cut largely in London Clay, forming broad, more-or-less flat, tracts of land on which most of central London is situated (figure 4).

During the last glacial (Devensian) episode in Britain which ended about 10,000 years ago, sea-level fell to around 100 metres lower than the present level. During this period the Thames in the London region cut down to a maximum of 15 m below present sea level. The subsequent rapid sea-level rise in the Holocene led to infilling of this valley and the development of localised "scour hollows" no more than 0.5 km in diameter that eroded up to 50 m into bedrock (figure 5). The precise timing and mechanism of scour formation and infilling is uncertain, but both the presence of ground ice and the effect of hydrostatic pressure in the Chalk have been suggested as possible causes (Berry, 1979; Hutchinson, 1980).

The present River Thames is tidal through London, retained by artificial flood embankments on a floodplain of alluvial deposits less than 0.5 km wide in the west and 3 km in the east.

Figure 3.—Simplified geology and cross-section of the London region. For key to the geological formations see figure 2.

Figure 2.—Generalized geological succession, not to scale, in the London region. Arrows indicate the stratigraphic position of geological surfaces entered into the computer database

Figure 4.—Distribution of the principal superficial deposits on the London region, and generalized cross-section.

Geological hazards and engineering practice

The London Clay is an excellent tunnelling medium, which greatly facilitated the rapid development of London's 656 km of tunnels. Owing to a variety of man-made and geological factors, it was, however, often difficult to confine the tunnels to the London Clay strata.

Many of the unforeseen engineering problems that arose in the course of tunnelling beneath London have resulted from a failure to predict correctly the rockhead level (base of the superficial deposits). On a number of occasions, excavators have encountered the rockhead surface whilst tunnelling through London Clay, and several hundred cubic metres of gravel and water have been flushed into the tunnel, creating serious subsidence cavities at the surface. Tunnelling beneath the Thames required particular precautions to prevent river water from flowing in and flooding the excavations. The "scour hollows" that penetrate far below the predicted upper surface of the London Clay can usually be recognised during detailed site investigations prior to engineering development, but sometimes even very dense borehole coverage has missed localised depressions, which are described by engineers as "funnelling down". Such deep drift-filled hollows were encountered in the course of a number of tunnelling projects and major building developments, for example at the Battersea Power Station and the Blackwall road tunnel. Chemical consolidation methods, ground-freezing techniques and working under compressed air have been invaluable aids when excavating

through water-saturated ground or cutting through unconsolidated strata.

Groundwater problems increase with depth, particularly where excavations encounter the Woolwich and Reading formations, which underlie the London Clay, as in an estimated 23 km of London Underground railway tunnels (Craig and Simpson, 1990). Tunnel lining usually consists of cast-iron segments or reinforced-concrete segments, with modern practice favouring concrete segments expanded into close contact with the rock strata. The presence of pyrite and gypsum, particularly in the London Clay and in places in the other Palaeogene formations, has locally increased the sulphate and sulphuric acid levels in the groundwater, and some reaction has taken place with tunnel linings. This problem of acidic groundwater in contact with concrete structures is likely to be exacerbated in the future, as the widespread cessation of water abstraction from deep boreholes is causing groundwater levels in central London to rise at a rate of up to 1 m annually.

London Clay has a medium-to-high shrinkage potential (Driscoll, 1983) and this is reflected in the relatively high incidence of subsidence recorded from properties sited on London Clay, most of which lie within the suburban belts surrounding London. Following the serious drought in the summer of 1976, widespread structural damage was recorded from buildings sited on London Clay, and as a consequence building regulations were modified to ensure that typical house foundations were increased in depth.

In the London area, landslipping is a geological hazard mainly on London Clay slopes, particularly in the sandier upper part of the formation where springs are common and when these hillslopes are greater than 7°. It is not unusual for there to be minor landslips on man-made slopes such as railway cuttings through London Clay, many years after excavation.

Subsidence into dissolution hollows and man-made workings is a well-known geological hazard affecting the Chalk outcrop and areas where the top of the Chalk is near the surface.

The severe storm surge of 1953, which flooded many parts of the east coast of England and areas of London, emphasised the need to protect low-lying ground by strengthening sea defences in the region. The major element in this strategy was the Thames Barrier (figure 1), which is a structure comprising movable gates that can be closed when exceptionally high tides are expected (Wakeling and Jennings, 1979). It extends across the Thames at Woolwich Reach. Essential to the success of the project was the improvement of the sea-defence embankments bordering the Thames downstream of the barrier. Concerns about global warming and rising sea levels, linked with the possibility that southeast England is gradually sinking, have increased the awareness of the long-term risk of flooding.

Digital geological map development

The earliest systematic geological mapping of London was carried out by the Geological Survey in the 1860s at one inch to one mile, and the results were published as descriptive memoirs (Whitaker, 1872; 1889). Between 1900 and 1930, surveys at six inches to one mile (1:10,560) led to four one-inch maps (sheets 256, 257, 270 and 271) and their respective descriptive memoirs (Bromehead, 1925; Dines and Edmunds, 1925; Dewey and Bromehead, 1925; Dewey, Bromehead, Chatwin and Dines, 1924) that covered the whole of greater London (figure 1).

With the increasing demand for urban geoscience information, BGS has developed a digital map-production system (Nickless and Jackson, 1993). The first digitally produced maps at 1:10,000 with full geological attribution are now available for the North London area. The current project will complete digital cover for the whole of London, including the East Thames Corridor (figure 1). This corridor is an important area for development, which is likely to be stimulated by infrastructure improvements associated with the imminent opening of the Channel Tunnel linking England and France and the proposed high-speed rail connection with London.

The digital map system holds geologically attributed (or vectorised) spatial information. It can routinely produce on demand up-to-date colour-printed geological maps at any scale. Importantly, the attribution of geological information facilitates the production of thematic maps illustrating combinations of geological and non-geological elements (e.g. areas of sand and gravel; man-made ground; the routes of major highway projects). The output consists of coloured maps on paper and digital data that can be used for GIS applications. One of the great advantages of these digital maps is that they can be produced for irregular-shaped areas covering, for example, administrative regions or route corridors that may include parts of one or more "standard" (rectilinear) maps.

Borehole information

The British Geological Survey holds more than 20,000 borehole records from the London region. Most are of site investigation boreholes drilled in the last 50 years to depths generally between 10 and 40 m; several hundred, many drilled in the last century, are of water wells into the Cretaceous Chalk. About 20 of the boreholes are more than 300 m deep and prove the pre-Permian basement (Allsop and Smith, 1988). Samples from many of the boreholes proving the basement are curated in the BGS borehole-core collection. In addition, complete cores and/or representative samples from 19 boreholes proving the succession of Palaeogene strata are curated. Since there are few well-exposed permanent sections in the region, these cores are the reference sections for many of the Palaeogene formations and are used to assist in interpreting borehole logs where no material is available for examination.

In order to assess the geology of the London region, four horizons that can be easily recognised in borehole records (figure 2) have been selected for entry into a database which contains the depths of these horizons with respect to sea level. This has enabled a synthesis of the vast quantity of data in the borehole records to be made, and the available information to be reduced manageable proportions.

The highest surface used is the base of man-made ground, which includes the fill of pits, quarries and other excavations, and waste deposits tipped onto formerly undisturbed ground. The depth to base of these deposits in former pits is highly irregular and hence meaningless and impractical to contour. The distribution of significant areas of man-made ground and the thickness proved in boreholes (shown as point data) are produced on thematic maps, along with information about the use of the site.

The second surface is the base of the superficial deposits. In London these comprise the unconsolidated alluvial silts, clays and peat of the modern floodplain, and river-terrace sand and gravel deposits. The alluvial deposits are too soft for foundations and the depth to their base must be determined at all development sites. The terrace deposits are a valuable aggregate resource, although most are exhausted or built over. The terrace base is generally planar, although there are restricted overdeepened hollows (scours), some of which penetrate the base of the London Clay or even the top of the Chalk, filled with unconsolidated saturated sands, silts and gravels.

The third surface is the base of the London Clay. The London Clay underlies the drift deposits in much of London, and as it is strong and generally homogeneous, most of the larger buildings in central London are built on piles drilled through the superficial deposits into the London Clay. The strata are usually well defined in borehole records, particularly as the underlying beds are contrasting soft sands, silts and clays of the Woolwich, Reading, Upnor and Thanet Sand formations. As these underlying beds can be in hydraulic continuity with the underlying Chalk, both their rapid lateral and vertical variation and also the water content pose problems in tunnelling and foundations.

The lowest surface, the top of the Cretaceous Chalk, is important as the Chalk is a major aquifer. It is essential therefore to be able to predict where site investigation boreholes or any construction activity will encounter Chalk in order to minimise the risk of ground-water pollution.

Digital borehole database

The Project has established a digital, relational borehole database. This digital resource is founded on the paper records of wells and site-investigation information currently held in the BGS national archive. The records are checked for accuracy of location and height with respect to sea level and geologically classified, and these enhanced data are encoded into digital form.

Quality assurance

Quality assurance (QA) checks are an integral part of the databasing procedure, which currently follows an internal BGS quality assurance guide (compatible with the British Standard 5750:1987).

For example, checks of the borehole grid coordinates ensure that they correspond with the plotted position on the site maps and with the site description. Reliability values of the raw borehole data are systematically entered into the database. Demonstrably unreliable borehole records are not entered into the database. The QA appraisal imposes reliability codings on five parameters relating to the borehole record:

- Accuracy of grid coordinates
- Reliability of the borehole log
- Accuracy of the Ordnance Datum
- Reliability of the stratigraphical classification
- Reliability of the recorded depths in the borehole log

Using the reliability factors, information of a specific quality can be selected from the relational database. The digital information is refined as computer modelling proceeds, and anomalous data are reassessed and either corrected and re-entered or discarded. The process involves a number of iterations, dependent on the complexity of the geological surface being modelled, until a geologically satisfactory result is achieved.

Data processing

The data are processed on the Natural Environment Research Council (NERC) Vax 8550 and 6510 mainframe computer cluster on the BGS campus, using the following software packages (figure 5):

- ORACLE—a relational database management system used to store, retrieve and manipulate data (Oracle, 1990);
- GRAPHLOG—a BGS-developed program (Flower, 1987) used to produce graphical borehole logs for easy reference purposes (available on-screen and as paper copy);
- ISM (Version 7)—Interactive Surface Modelling: software designed and marketed by Dynamic Graphics (1990). It is used for gridding, contouring, drawing cross-sections and perspective block diagrams.

Recent developments in computer processing have led to the data's being modelled on stand-alone workstations. Two software packages are under trial, both run on Silicon Graphics Indigo 3000 workstations:

- EARTHVISION—workstation-based, and marketed by Dynamic Graphics (1992). This package combines the facilities of ISM with another Dynamics Graphics product, Interactive Volume Modelling (IVM);

Figure 5.—LOCUS Project computer modelling flowchart.

Figure 6.—Contours on the rockhead surface in part of central London. Contours are at 2 m intervals in metres relative to Ordnance Datum (sea level). Stippled areas indicate London Clay at outcrop.

levels where the (geological) surface is known to be absent.

By combining data from geological maps and the borehole database, and by the use of appropriate computer modelling software, the data may be interrogated, manipulated and corrected to produce geological models consistent with the known surface geology.

Computer-generated geological data

One example of a computer-generated contour plot, the base of the superficial deposits (rockhead), is shown on figure 6. Similar plots are produced for each modelled surface. Such computer-generated surfaces can be displayed as perspective views (figure 7) from any chosen vantage point (thus giving a 3-D appreciation of the structure), and cross-sections can be drawn along any line (figure 8), showing all the surfaces that are modelled.

In summary the database and software provides:

- Borehole listings
- Graphical representation of borehole logs (GRAPHLOGS)
- Distribution plots of borehole sites
- Contour models
- Isopachyte (thickness) plots of major geological units
- Cross-sections and fence diagrams
- Perspective views
- Block diagrams.

Conclusion

The methodology for dealing with large volumes of geological data has been established for the London region. Implementation of digital map production and the rationalisation of data, principally borehole data, has enabled routine production of computer-generated geological models of London and the means to visualise automatically a range of information from point data to 3-D models.

The geological understanding of the ground underlying urban areas that comes from geological surveying and the modelling of borehole data is of particular use for:

Figure 7.—Example of a computer-generated perspective view of the top of Chalk in central London (viewed from the north-east). Depths are in metres.

● VULCAN-ENVISAGE—workstation-based (Vulcan, 1992).

Data are retrieved from the ORACLE database into files suitable for use in the modelling software. Four file types are used: scattered data files for point information; fault data files that contain digitised fault-plane information; polygon files that include, for example, areas of outcrop of a particular geological formation; and annotation files that contain digital topographical information.

Although it is possible to compute displays and perform various analytical tasks directly from scattered data, the modelling software uses these data and a gridding algo-

rithm to calculate surface grids. For computational purposes, a surface is generated by using the algorithm to calculate the height of the surface at a theoretically unlimited number of other points. In practice a grid with nodes at 10 m or 20 m spacing is used. These grids provide the basis for subsequent modelling and geological analysis.

One of the ISM options used in this work permits the use of the full dataset in the grid calculation. This means that in calculating a particular surface, both boreholes that prove the surface and those that do not prove it are used. This constrains the gridding and prevents the gridded surface rising above

Figure 8.—Example of computer-generated geological cross-section in central London.

- Resource exploration and exploitation
- Construction and civil engineering
- Land-use planning
- Hazard assessment
- Waste disposal
- Pollution protection.

The similarity of the basic geology of many of the world's conurbations (i.e. unconsolidated superficial deposits overlying bed-rock that is more suitable than the cover for foundations and excavations) leads us to believe that the methods adopted for London could be applied elsewhere, to the benefit of planning and development.

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Stephen Booth is a Principal Geologist with more than 20 years' experience in the Land Survey of the British Geological Survey. He is currently responsible for databasing, computer modelling and GIS for the LOCUS project. In addition to assessing industrial minerals including Carboniferous coal, Quaternary sands and gravels and Triassic evaporites, he has also undertaken geological mapping both in the United Kingdom, including Quaternary deposits in East Anglia, and overseas in the Solomon Islands, Western Pacific, prospecting for gold and copper in Tertiary and Quaternary island-arc volcanics.

Poul Strange is a Principal Geologist in the British Geological Survey. He joined the Survey in 1972, and has undertaken geological mapping in England, Bolivia and the Solomon Islands. In 1983 Mr Strange was seconded to the Hong Kong government as a geotechnical engineer, specialising in urban geological mapping. He was head of the Hong Kong Geological Survey between 1988 and 1991. Besides producing new geological maps of the Territory, he has written a number of memoirs and papers on the geology of Hong Kong. Mr Strange now works with the LOCUS team, revising the geological maps of London.