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The investigation of dissolution subsidence incorporating microgravity geophysics at Ripon, Yorkshire

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Abstract

Dissolution subsidence affords some of the most difficult ground conditions with which engineering geologists have to deal. Within the UK, areas underlain by gypsiferous Permo-Triassic strata, most notably around Ripon in Yorkshire, are prone to dissolution structures and resultant building failures are well documented.

Conventional drilling of such unstable sites is often a 'hit and miss' affair and most geophysical techniques do not provide sufficient resolution to offer adequate confidence in the results. Proposals for the redevelopment of a site within the urban area at Ripon could not rely on such frequently inconclusive methods and it was necessary to implement a phased approach to site investigation. Following a desk study, high-resolution microgravity geophysics was carried out both inside and outside the existing building. This indicated a major negative anomaly of peak amplitude $-74\ \mu$Gal. Subsequent static core probing, rotary drilling and trial trenching confirmed the existence of a potentially unstable breccia pipe which could therefore be taken into account in the engineering design.

Introduction

Since the early records of subsidence in the vicinity of Ripon by the Reverend J. S. Tute in 1868, it has been known that much of the area may be unstable. Cooper (1986, 1989) has catalogued catastrophic subsidence on more than 40 occasions in the past 150 years which resulted from the dissolution of gypsum in Permo-Triassic strata. In Yorkshire, a subsidence-prone belt extends from near Bedale, southwards through Ripon, to south of Doncaster. Northwards, it extends through to Darlington and Teesside (Smith 1972; Cooper 1986). It may also be present to the southeast of Carlisle and in the Vale of Eden (Sherlock & Smith 1938; Ryder & Cooper 1993). In the Midlands, subsidence is not extensively documented but some gypsum karst features have been recorded southwest of Nottingham (Wynne 1906; Smith 1918). Similar ground problems have been recognized throughout Europe and North America (Cooper 1986). Thus the approach to ground investigation at Ripon has relevance to a very extensive area.

With such complex ground engineering problems, a major concern of the Property Services Agency in examining proposals for a new Government office development was the design of investigations to determine the true ground profile and the resolution of any phenomena detrimental to construction. A logically phased approach had to be implemented. This paper describes this approach, the results of a microgravity survey and subsequent investigations, and discusses their effectiveness in determining the required engineering of the site.

Geology of the Ripon area and nature of subsidence

The Ripon area comprises a complex succession of glacial and post-glacial deposits overlying gypsiferous Permian strata (Fig. 1), details of which are discussed by Cooper (1986, 1989). Gypsum sequences occur in the Edlington and Roxby Formations (formerly called the Middle and Upper Marls) where they are respectively up to 40 m and 10 m in thickness. Those in the Edlington Formation are sandwiched between the aquifers of the Cadeby and Brotherton Formations (formerly the Lower and Upper Magnesian Limestones) which afford large volumes of groundwater for gypsum dissolution.

Caves are developed in both the Edlington and Roxby Formations with the largest caverns believed to occur at the intersection of major joints in a similar manner to those observed in the Vale of Eden (Ryder & Cooper 1993). Catastrophic collapses follow the rectilinear pattern of joints and migrate to the surface as breccia pipes. The lack of bulking associated with the soft Permo-Triassic strata results in even small cavities

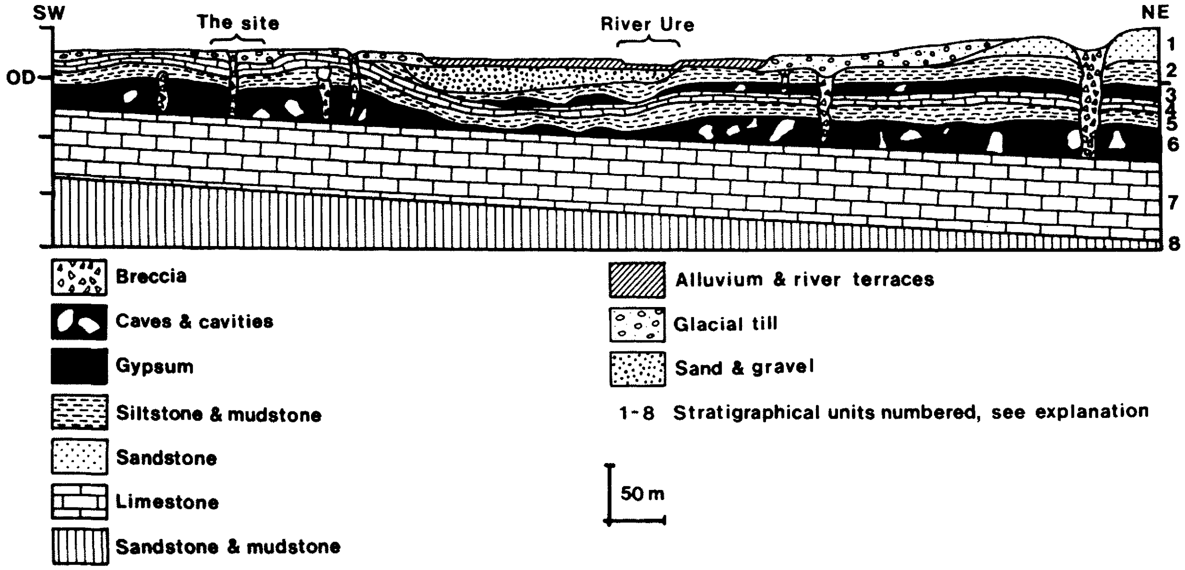

FIG. 1. SW–NE cross section through the Ripon site and across the River Ure, slightly stylized but based on about 20 boreholes in the vicinity. 1, Sherwood Sandstone Group; 2, Roxby Formation; 3, Gypsum in the Roxby Formation; 4, Brotherton Formation; 5, Edlington Formation; 6, Gypsum in the Edlington Formation; 7, Cadeby Formation; 8, Carboniferous strata. Also illustrated is the development of caves in the gypsum sequences and their upward propagation as breccia pipes. Numerous ages of breccia pipes are shown, some filled with glacial deposits, others only recently breaking the surface.

propagating through the sequence (Cooper 1988).

Subsidence has occurred since glacial times and numerous deep subsidence hollows, partially or completely filled with soft clays and peat, are found in the Ripon area. Two main types of poor foundation conditions may occur: (i) caves which have not yet collapsed and (ii) unevenly compressible materials in breccia pipes, crown holes and subsidence hollows.

Such conditions have resulted in the collapse of numerous buildings around the city and much of the housing stock has suffered various degrees of distress (Fig. 2) (Griffin 1986). In the past the worst areas have been largely avoided but modern pressures on land require more of the difficult areas to be considered for future development (Harrogate Borough Council 1992).

Current approach to site investigation

There has frequently been a lack of commitment to effective investigation in the subsidence-prone areas of Ripon, with only one or two boreholes of insufficient depth being drilled, even on fairly large sites. Such problems have been compounded by the common mistaken identification of gypsiferous drilling returns as limestone. In addition, the upper gypsum sequence resting on the Brotherton Formation is commonly misidentified as the lower gypsum sequence resting on the Cadeby Formation. Consequently, the lower thick gypsum sequence, which contains the most extensive dissolution features, is frequently unrecognized. Many of the drilling logs obtained for the area apparently record considerable thicknesses of limestone when adjacent ground contains voids with subsidence problems. The difficulty with conventional investigation is the number of boreholes required to delineate the complete problem. Even a closely spaced network can only be expected to identify the worst instabilities, often leaving small but structurally significant caves and breccia pipes undetected.

Geophysics has the potential to overcome many of the problems inherent in conventional physical investigations, but the more common techniques also have shortfalls. Cooper (1989) discussed the use of resistivity and EM31 conductivity studies around Hutton Conyers, near Ripon. Whilst the resistivity results indicated some anomalies, these were difficult to model and no significant void was found. The district was also surveyed using airborne multispectral scanning, but again with limited success since the technique provides no information in built-up areas.

On mainland Europe, in karstic, collapsed or otherwise voided ground, microgravity methods are frequently employed to identify zones of less dense material. Although the field data require sophisticated

FIG. 2. Subsidence hollow formed on 28th July 1979 behind houses on Magdalen's Road, Ripon (SE 3170 7129), 200 m SE of the site discussed. The garages which stood on the concrete slab had long shown signs of distress and were demolished prior to this catastrophic collapse (photo: Acrill Newspapers).

computer processing, the evolution of lap-top PCs now allows much of this to be completed before leaving the site. With the experience of successful deployment elsewhere it was decided to incorporate microgravity within the investigations for a new two storey Government office development with a floor area of about 11 000 m^2

Background to the use of microgravity geophysics

Microgravity surveys were largely developed in France where the first commercial application to civil engineering problems was undertaken in 1962, since when they have become a regular feature of site investigation contracts. Only since the 1980s has the technique grown in popularity in the UK.

Microgravity surveys offer many advantages. In particular they

- are applicable to a wide variety of ground conditions
- require no ground penetration
- are relatively unaffected by hard surfacing and underground services
- may be deployed within furnished buildings, thus allowing a redevelopment site to be investigated prior to vacant possession, or a narrow tunnel complex to be surveyed from the inside.

There are few disadvantages but perhaps not surprisingly for such a powerful technique, microgravity may be relatively expensive due to the high capital cost of equipment and the need for highly qualified and experienced operators.

The basic principles of a microgravity survey are the same as those for a conventional gravity survey and the same data processing stages must be carried out. The Lacoste and Romberg Model D microgravity meter is sensitive to 1 μGal (almost 1×10^{-9} of the Earth's gravitational attraction), an order of magnitude better than the Model G meter used on deep structural and petroleum studies, and allows very small variations to be identified over building plot sized sites.

Maintaining this high precision requires attention to instrument calibration and measurement consistency. Calibration of the meter must be made by both workshop procedures and measurements taken over a

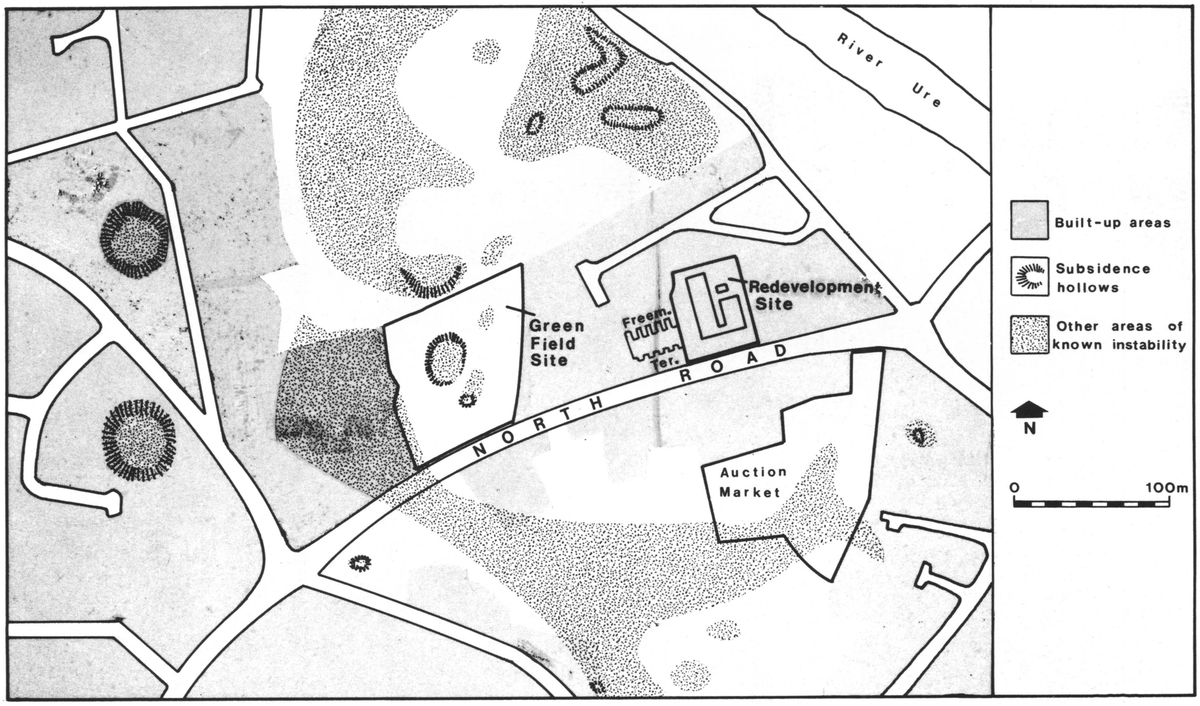

FIG. 3. Location plan showing that part of Ripon in the vicinity of the sites discussed, together with known subsidence features.

standard test range, daily checks made in the field with the instrument allowed to stabilize prior to each day's work, remeasurement of a site base station every 30–40 minutes and repeat measurements taken on a semi-random basis throughout the survey station grid. Microgravity readings should not be taken in high winds or during periods of excessive ground noise such as that caused by distant earthquakes, quarry blasting and percussion drilling (rotary drilling may only cause acceptable ground noise). All processing corrections must be made with corresponding precision and the levelling of microgravity stations also has to be undertaken with special care; a simple closing error is insufficient and many repeat measurements are made to obtain an accuracy of ±2 mm for each station elevation. Realistically achievable accuracy in the observed gravity is about 4 μGal but without care and attention, errors can quickly assume a significant proportion of any observed anomaly.

Detection is limited by the contrast in density between the target and the surrounding material. For example the density contrast between an air-filled cavity and limestone might be as high as 2.5 g/cm^3 whereas a loose backfilled cavity in sandstone might show a contrast as low as 0.2 g/cm^3. The size of the survey area, the accuracy of the processed data and the size of the target all limit void detectability. Assuming an accuracy of 4 μGal, it is possible to show that a void of 2 m radius and density contrast of 2.5 g/m^3 would not be resolved below a depth of 12 m. However, experience shows that natural collapse features are often surrounded by low-density zones which aid detectability so that much smaller voids often produce much stronger anomalies than might at first be expected. Our experience suggests that a high proportion of structures of engineering significance may be detected.

Accurate interpretation may be enhanced by preliminary modelling where existing site investigation data are available. Working back to give an estimate of the size and extent of the microgravity anomaly allows optimal design of the field measurement grid. In general, the amplitude of the anomaly decreases with depth while wavelength increases, thus necessitating a larger survey area with wider spaced reading intervals.

Recent phased investigations at Ripon

In examining the proposal for a new Government office development, studies were carried out at two separate sites (Fig. 3). Late in 1990 consideration was given to a

FIG. 4. Subsistence hollows on the greenfield site on the A61 North Road.

green field site of some 8000 m^2 alongside the A61 North Road. For initial assessment, a literature and plan search was undertaken together with a brief walkover survey. What were believed to be subsidence hollows were visible in the centre of the site (Fig. 4) and just beyond the northern site boundary. The same features were shown both on the First Edition Ordnance Survey maps of 1982 and on the recent airborne study (Cooper 1989).

Two existing borehole records confirmed the ground depression within the site to be the result of subsidence. One borehole located within the feature revealed about 9 m of soft clay and peat underlain by badly broken limestone, dolomite, gypsum and calcareous mudstone. Below 30 m to the base of the borehole at 35 m, relatively intact dolomitic limestone was reported. However, it was believed that unless the geological map was incorrect, this apparently competent stratum was gypsum rather than limestone. In the second borehole, located away from any obvious subsidence feature, a sequence of essentially granular glacial deposits extended to a depth of 12 m, where it was underlain by weathered and badly broken strata, again described as dolomitic limestones. In both boreholes, rotary and open hole techniques had been attempted, but only minimal sample recovery was obtained and hence only an extremely crude idea of strata integrity determined.

This site was clearly within the main subsidence area and it was believed that, in addition to the obvious subsidence hollow, other buried instabilities could be present. In order to identify the full range of ground conditions present, and particularly to find any portions of the site which might be considered stable, an extensive investigation programme would be required. At this time it was decided that such a programme and the possible foundation options would be extremely expensive for the small office development required.

Attention was then given to redeveloping the site of the existing Government offices some 120 m to the east. Although also within the subsidence area it had been stable for some time. The existing 50 year old building showed no sign of structural distress and most of the site was level. It was a much smaller site, 3000 m^2, and largely occupied by the offices and associated hardstanding areas. There were clear difficulties in carrying out an effective investigation without excessive disruption to the occupants of the offices, which had to remain open to the public during office hours, and disturbance to neighbouring retirement homes. Added to this, in the examination of a small site, the broader interpretation is less easy to resolve and various options for building location, to avoid the most unstable areas, are less readily available.

It was clear that any cost effective investigation of the second site would require a phased approach, in which the results from each stage could be reviewed before proceeding with subsequent exploration. The sequence of events and the results of each stage are discussed below.

Walkover survey

The walkover survey provided evidence of either dormant or active subsidence hollows in open fields 90 m north and 140 m west of the site. A near-by active subsidence hollow, behind the Auction Market on the opposite side of North Road, is periodically levelled up with stone, and a number of properties in the immediate area are damaged or tilted. Freemantle Terrace, a line of red brick four-storey Victorian properties which abuts the site, only exhibited some slight cracking to lintels and brickwork along their rear elevations.

No record came to light of any earlier development of the site or other subsidence features but the sudden termination of the development at Freemantle Terrace, compared to the continuation of similar properties on the opposite side of North Road, was noted with interest.

Geophysical survey

With instabilities present in the vicinity, the likelihood of past, but unrecorded subsidence on the site could not be ignored. From previous experience it was considered that certain geophysical methods might be employed to advantage.

The existing development ruled out comprehensive coverage by any technique other than microgravity, although because of uncertainty in the location of services, shallow electromagnetic measurements were first made across the lawns along the western and southern boundaries of the site. All major services entering the area were accurately located for future reference and a relatively low conductivity zone, 16–25 mS/m, was identified to the west of the building, perhaps indicative of improved drainage resulting from broken strata at depth.

For the microgravity survey, a primary grid 8 m×8 m, with alternate lines offset by 4 m to improve overall coverage, was established throughout the site using a variety of markers; spray paint in the car park, wooden survey pegs in the grounds and chalk marks on the office carpets! Marking out, levelling and exterior microgravity readings were undertaken during office hours with the interior readings being left to evenings and weekends when office floor vibrations would be minimal. Preliminary processing of each day's measurements was undertaken at the field base and intermediate stations were established and read where substantial variations between adjacent points on the primary grid were observed.

The network of stations was extended beyond the site boundaries to permit correction of regional gravity variation. Instrument drift was identified by regular repeat readings at a selected base station and by semi-random returns to other stations within the grid while lunisolar drift was computed by standard procedures. Standard Bouguer corrections were applied to the field data. The base station and a selection of primary grid measurements were repeated to facilitate iterative drift control and close quality control; these comprised 44% of the total readings. Statistical analysis of the repeated station values showed the root mean squared error in the observed gravity to be 3.7 μGal. Assuming a Gaussian distribution, approximately 67% of the readings would have an error less than this. Possible causes of such variations in repeat readings could be microtares to the meter caused by strong winds or temperature changes, instrument levelling errors or incorrect drift adjustment. Errors that cannot be detected by repeat readings result from use of an incorrect reduction density, elevation and terrain variations but these largely cause systematic errors which are unlikely to have a significant effect on the interpretation.

Subsequent data processing included corrections at thirteen stations within the building and eight close to its external walls for the gravitational attraction arising from the mass of the existing structure. Readings taken within the building also required additional Bouguer slab corrections to compensate for the type of flooring e.g. floorboards above a void will require different correction to a concrete ground slab.

The processed data were contoured to yield a Bouguer anomaly map. This showed small negative anomalies superimposed on a regional gradient thought likely to result from the gentle dip of the strata to the east. The form of the regional gradient is determined interactively, partly in the field and partly in the office, to produce residual anomalies which, from experience and a knowledge of the geology and the particular engineering problem, are likely to be significant in engineering terms. In this case, the resulting residual map (Fig. 5) indicates the positions of any gravity lows which might be related to collapse features.

Over most of the site, residual gravity values fell within the range -20 to $+20$ μGal and as in Area A on Fig. 5, commonly reflect generally stable conditions. In addition, there were three areas of more negative values, where less dense ground could be expected. In two of these, Areas B and C to the north and southeast of the

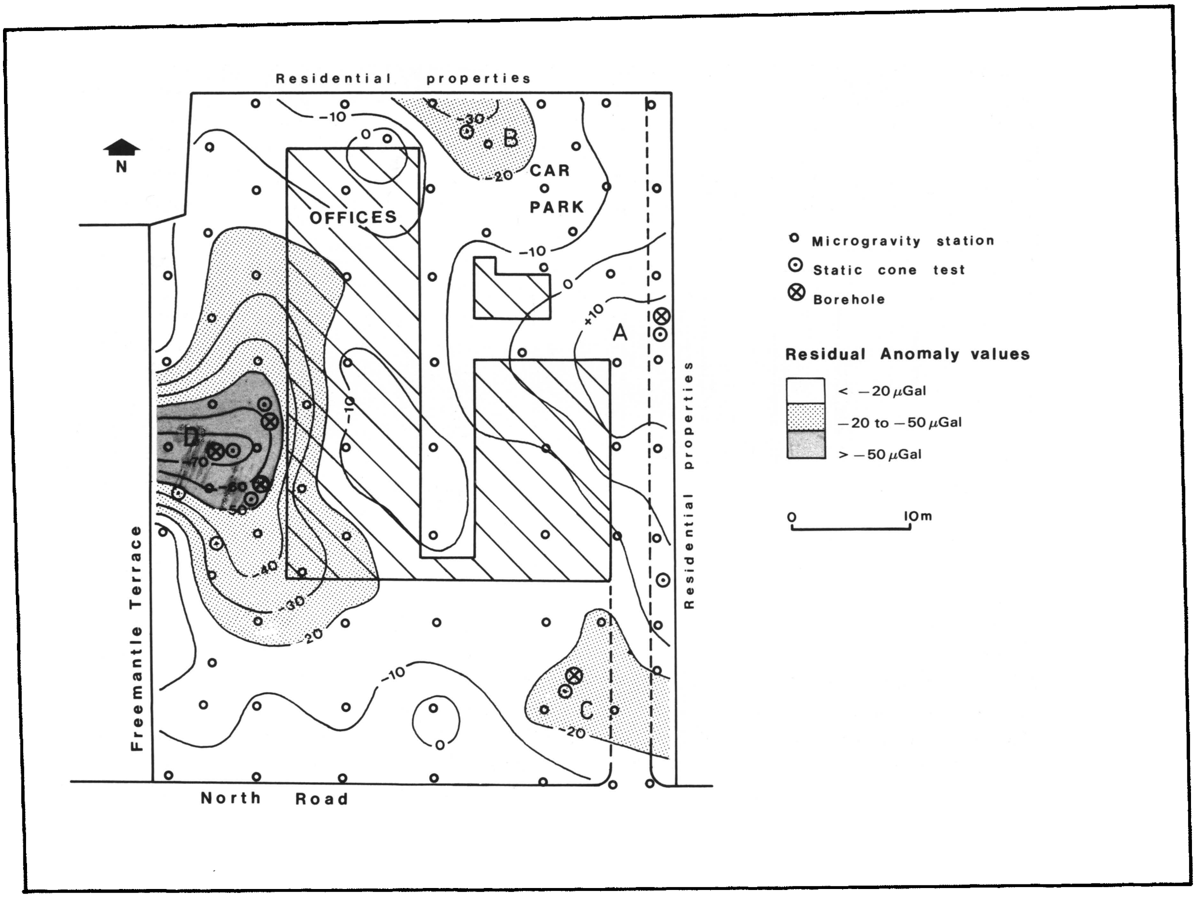

FIG. 5. Plan of the redevelopment site showing the microgravity results, core penetrometer test and borehole locations.

site, values dropped to −30 μGal and, whilst possibly indicating some disturbed ground or an increase in post-glacial cover, the anomalies were not thought to indicate that extraordinary engineering problems would be met. They may have represented the extremities of more significant anomalies located beyond the site boundaries. The third, and largest, of these negative zones, on the west side of the site (Area D on Fig. 5), gave values below −40 μGal over a broad area, dropping to −74 μGal in the centre of the anomaly. Preliminary gravity modelling suggested a reduction in density by as much as 0.5 g/cm^3 in the central 5 m or so.

Figure 6 illustrates a more complex model, where selected features are modelled in three dimensions, made after drilling and prior to trenching.

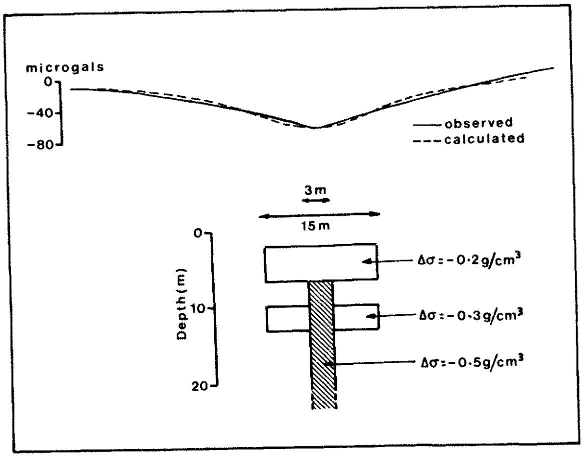

FIG. 6. Basic gravity model used to interpret the observed residual anomaly, proved by subsequent physical investigation to be substantially correct.

Physical investigations

The purpose of the physical investigations was to provide control data on the ground conditions, to

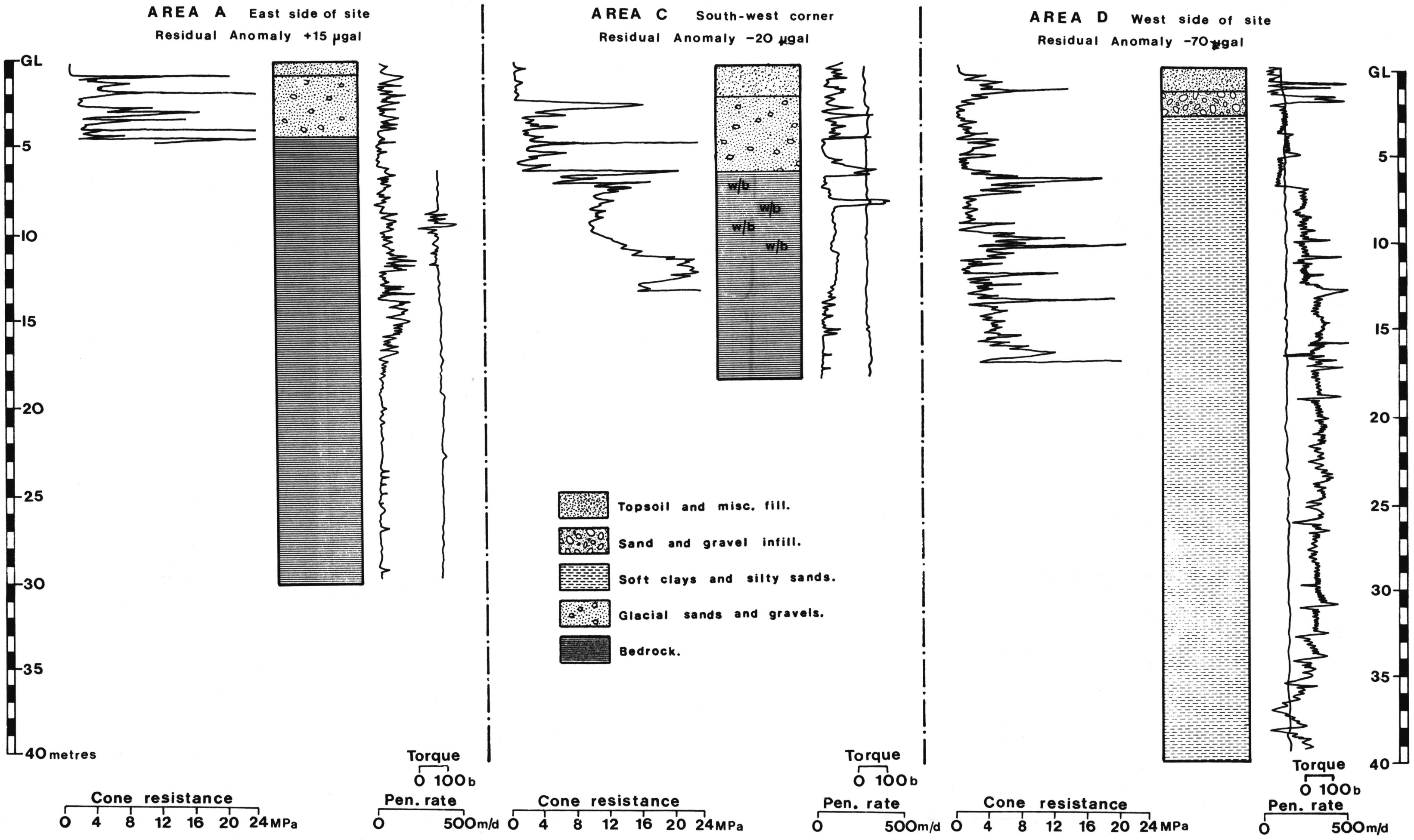

FIG. 7. Geological logs together with CPT drilling torque and rate of penetration results for selected areas within the redevelopment site.

refine assumptions made in the geophysical model and to obtain sufficient information for stability analysis and foundation design. After careful consideration of the available options, three investigative methods were ultimately deployed; static cone penetration testing, rotary open hole boring with 'logging-whilst-drilling' (LWD), and trial trenching. These investigations were themselves phased, the order in which they were deployed being based on the type of data acquired, disruption to the occupiers and residents, and cost.

The results of the static cone and drilling investigations (Fig. 6) confirmed that the geology of the site generally conformed to the published stratigraphy of the area and that the location and dimensions of anomalies had been well defined by the microgravity survey.

Beneath the typically thin topsoil and some 1.7 m of assorted fill, the glacial drift comprised loose, becoming dense, sands and gravels with some gravelly sands and firm to stiff sandy silty clays. Most of the static cone tests met with refusal at less than 9 m depth within the drift deposits in very dense or hard material; this may be associated with localized secondary calcitic cementation, as suggested by other investigations in the area, and/or with an increase in particle size. These refusals included four of the five tests undertaken in the area of the major microgravity anomaly. Had the investigation ceased here and without the benefit of previous geophysics, this anomalous feature is unlikely to have received further attention.

The majority of boreholes drilled encountered limestone bedrock at depths of 11.5 to 13.6 m. This was generally moderately strong to strong but frequently contained clay partings or weak marl bands. Whereas most boreholes were taken to a depth sufficient to prove a thickness of limestone between 2.5 and 4.9 m, the control borehole on the eastern site boundary was drilled to a depth of 30 m. The LWD data suggested that marls occurred below 26.4 m, making the Brotherton Limestone Formation at this location 14.4 m thick. This roughly accords with its thickness proved locally in cored boreholes.

Comparison between the control borehole records and those obtained from drilling in the southwest corner of the site showed that the microgravity anomaly here reflected lower density drift cover over more highly weathered and slightly more broken limestones. This was considered to be either a minor geological variation limited to this area only or the 'edge-effects' of a larger collapse feature beyond the site boundaries. Either interpretation was considered to have limited impact on the proposed redevelopment and any resulting difficulties would be resolved by appropriate foundation design.

Both penetration testing and drilling of the major microgravity anomaly confirmed its association with substantial geological instability. At its centre, the dissolution collapse had become infilled with at least 40 m of loose sands, silts, and clays with some organic material and occasional gravels. The lack of any surface expression of this feature was explained by the presence of up to 3 m of fill material. The gravity model (Fig. 7) postulated for the structure was shown to be substantially correct.

Investigation was completed by trenching across this area in order to obtain additional information on near-surface conditions, collapse geometry, and recent subsidence history. The composite profile of this feature derived from this exercise is shown in Fig. 8. The feature was found to comprise a relatively narrow collapse 'pipe' within a larger depression in the normal near-surface succession which itself had become infilled with alluvial and fill materials. The pipe was shown to be no more than about 3 m in width along its north–south axis but at least 6 m wide along its east–west axis and may well extend beyond the site to the rear of Freemantle Terrace as did the near-surface hollow. Such an east–west orientation characterizes many of the dissolution features in the Ripon area (Cooper 1986).

The 'cone of collapse' that can develop from a void migrating upwards through superficial granular strata is normally determined by the angle of internal shearing resistance of the stratum. It has been demonstrated by the present study that with knowledge of the pipe dimensions at rockhead and adoption of a realistic angle of internal shearing resistance for the drift cover, in this instance 50° based on grading and density measurements, all the recorded ground anomalies, geological and geophysical, lie within the prescribed cone of collapse.

The distribution and composition of the fill materials in the uppermost 3 m of the feature revealed its recent subsidence history. Almost directly above the 'pipe' was an inverted cone infilled with clean well graded sand and gravel hardcore. The interface between this and the underlying laminated clays and silts was only slightly weathered and had a uniform slope angle of 20°. The lamination of the clays and silts tended to parallel the interface. Above the hardcore and around its margins an assortment of building rubble was mixed with the near-surface alluvial and drift material.

From this and a knowledge of the recent history of the area, it has been postulated that development work some 50 years ago for the existing offices caused up to 3 m of rapid settlement within the collapse pipe which was backfilled with hardcore at that time. Since there is no buried topsoil, it appears that the site was stripped to a shallow depth before this settlement. Indeed, it is likely that collapse was propagated by construction traffic vibration and/or surcharge loading. There is no evidence of any significant movement since infilling and re-levelling. It is believed that the pipe and the broader subsidence hollow are old features which had effectively reached a state of equilibrium in the latter stages of alluvial infilling but had become de-stabilized during

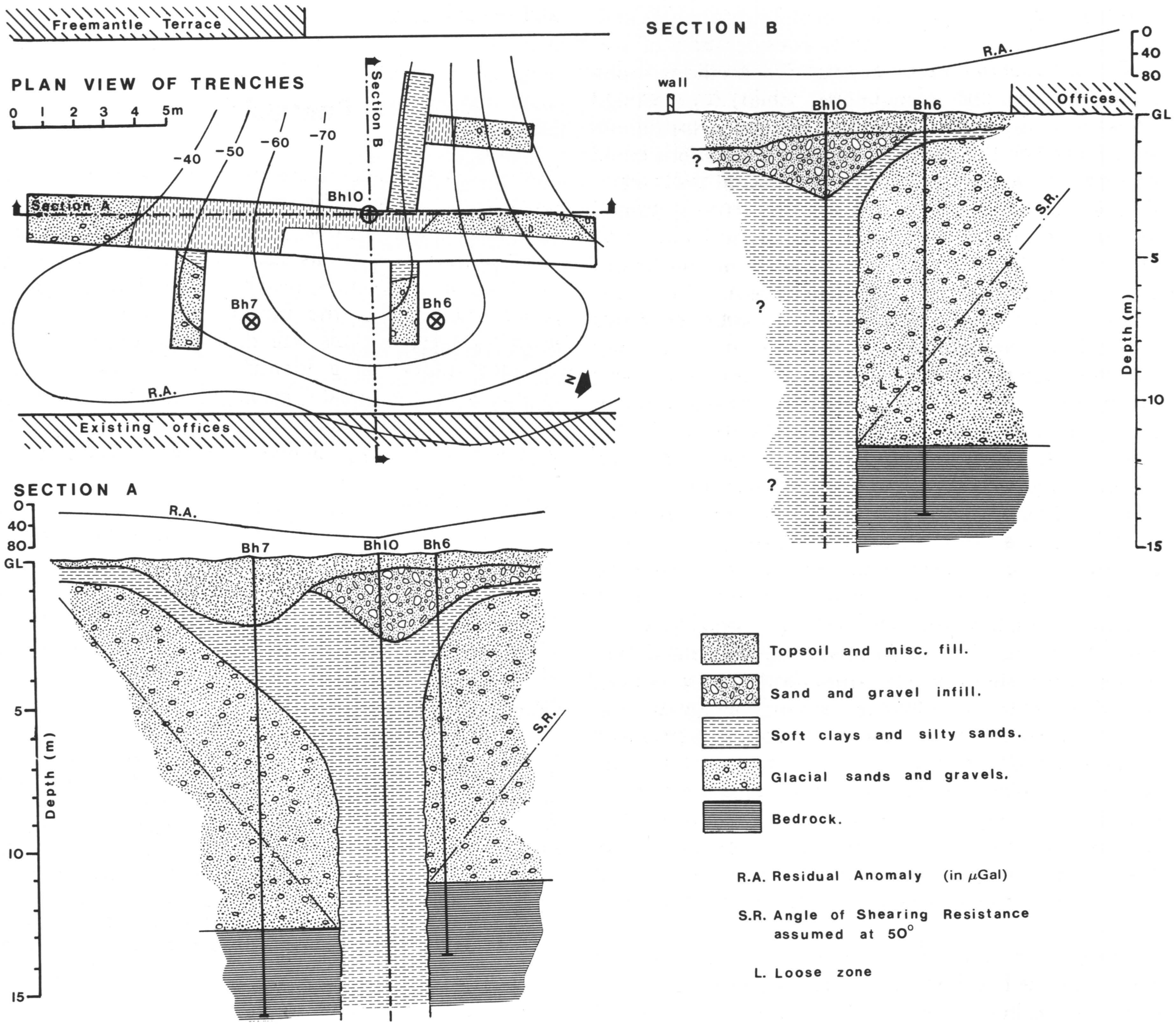

FIG. 8. Results of the trenching exercise across the subsidence feature identified on the redevelopment site.

construction of the existing building. Further collapse during future redevelopment would be entirely feasible.

Considerations for future foundation engineering

Whilst previous investigations have shown the complexity of ground conditions in the Ripon area, none has been able to provide a model upon which reliable conclusions or development strategy may be based. The recent investigations, utilizing microgravity geophysics as part of a logically phased approach to site investigation, have shown how complex conditions may be reliably interpreted and how a development strategy can evolve.

By the use of a reliable model of the ground conditions within a given site the intention should be to delineate the following:

- areas where dissolution and ground settlement remain active
- areas where dissolution subsidence has taken place in the past and poor ground conditions remain in subsidence hollows or pipes. While no longer active, such features may become de-stabilized by changes in the groundwater flow regime, by surcharging of the surface, by vibration, or by other influences.
- areas which are currently in a stable condition but

where dissolution subsidence cannot be ruled out in the future.

To place foundations on any part of a given site with a reasonable assurance of long-term stability requires load transfer to the Cadeby Formation. For most of the subsidence belt this is clearly unrealistic since this could only be achieved by installing piles to considerable depth through a combination of unstable cavernous ground and strong rock. Such piles would have to be designed against the effects of negative skin friction and loss of lateral support for much of their length. Among the alternative techniques that have been considered was 'ground improvement' by methods such as pressure grouting. However, the possible presence of organic material at depth in collapse features, the uncertainties that accompany the infilling of substantial voids, the possible effects on the groundwater regime and on adjacent land would tend to preclude such options.

The redevelopment strategy adopted, and suggested for other similar sites, has been principally to consider a minimum impact scheme with the aim of placing the structure in an area currently considered to be stable and to adopt a shallow foundation design imposing a low ground-bearing pressure. It has to be recognized that through alteration of the groundwater flow regime, caused by external influences as well as by natural changes, there is a finite time over which any given site within a subsidence-prone area may remain stable. In an attempt to safeguard against such changes, an element of rigidity, e.g. reinforcement to allow the foundation to span or cantilever over a settlement feature which may develop, and the possible inclusion of jacking points to allow re-levelling may be incorporated in the foundation design.

The strategy outlined above is of course somewhat idealized since it is likely, for reasons outside the control of the geotechnical adviser, that a given development may have to be partially sited over an unstable feature, either current or historic. In such circumstances consideration would need to be given to spanning or cantilevering the structure across the unstable ground. Material on the margins of a collapse pipe but within a broader subsidence hollow may also have to be 'strengthened' or supported. This has to be reviewed on an individual site basis. Where this arose at the existing Government office site, consideration was given to diaphragm walling, ground anchors and soil nails combined with surface protection to pedestrians (e.g. a geotextile 'catch net'), a flexible surfacing, and other engineering options.

The wider application of microgravity geophysics in this form of investigation would tend to reduce the only significant disadvantage of the technique, which is cost. The perceived high cost has, however, to be compared against the value of the data and the direct savings that can be made in physical investigations, and ultimately, building failure, associated temporary accommodation and remediation.

Conclusions

The phased approach to the investigation of the existing Government office site in Ripon has successfully determined the various ground conditions present. Most importantly, it has succeeded in fully delimiting an area of substantial instability. Had investigation proceeded without the initial use of microgravity geophysics, there seems little doubt that the chances of this instability being identified by a conventional approach were minimal. This might have led to a major claims situation, the need for redesign and remediation, together with long delays in the completion of construction.

The geophysical results clearly pointed the way forward and the phased approach to the whole exercise enabled the optimization of each method deployed to achieve a successful result, both efficiently and cost effectively. It is believed that the investigations described provide a realistic model for future work in Ripon and other subsidence-prone areas to enable their full potential to be realized.

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